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# रेलवे रोलिंग स्टाक पर संस्थापित पावर कनवरटर

## भाग 2 अतिरिक्त तकनीकी सूचना

*Indian Standard*

# POWER CONVERTORS INSTALLED ON BOARD RAILWAY ROLLING STOCK

## PART 2 ADDITIONAL TECHNICAL INFORMATION

ICS 29.200; 29.280

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

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Power Electronics Sectional Committee, ET 31

## NATIONAL FOREWORD

This Indian Standard ( Part 2 ) which is identical with IEC 61287-2 ( 2001 ) 'Power convertors installed on board railway rolling stock — Part 2 : Additional technical information' issued by the International Electrotechnical Commission ( IEC ) was adopted by the Bureau of Indian Standards on the recommendation of the Power Electronics Sectional Committee and approval of the Electrotechnical Division Council.

The text of IEC Standard has been approved as suitable for publication as Indian Standard without deviations. Certain conventions are not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'; and

b) Comma ( , ) has been used as a decimal marker while in Indian Standards, the current practice is to use a point ( . ) as the decimal marker.

Only the English text in the IEC Publication has been retained while adopting it in this Indian Standard, and as such the page numbers have been given afresh here since they are not the same as in IEC Publication.

## CROSS REFERENCES

In this adopted standard, reference appears to the following International Standard for which Indian Standard also exists. The corresponding Indian Standard which is to be substituted in its respective place is listed below along with its degree of equivalence for the edition indicated:

| *International Standard* | *Corresponding Indian Standard* | *Degree of Equivalence* |
|---|---|---|
| IEC 61287-1 ( 1995 ) Power convertors installed on board rolling stock — Part 1 : Characteristics and test methods | IS 15199 ( Part 1 ) : 2002 Power convertors installed on board rolling stock: Part 1 Characteristics and test methods | Identical |

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values ( *revised* )'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

*Indian Standard*

# POWER CONVERTORS INSTALLED ON BOARD RAILWAY ROLLING STOCK

## PART 2 ADDITIONAL TECHNICAL INFORMATION

## 1 Scope and general aspects

### 1.1 Scope

This technical specification shows basic circuit configurations, control methods, operation modes and behaviour of electric power convertors for rolling stock such as external commutated rectifiers, self-commutated rectifiers, choppers and inverters. It describes typical charts and methods, but does not claim to be exhaustive.

This technical specification is intended to provide supplementary technical information in the standards of the IEC 61287 series.

The main purpose of this specification is to calculate power quantities such as input/output voltage, input/output current, frequency spectrum of voltage/current, voltage/current ripple and voltage/current harmonics.

### 1.2 Convertor categories

The following convertors, whose fundamental structures are given in 1.4, are described in this specification:

a) direct convertors:
   1) external commutated rectifiers;
   2) self-commutated rectifiers;
   3) choppers;
   4) inverters;
b) indirect convertors;
c) convertors for multi-supply rolling stock.

### 1.3 Technical information

The items of each convertor in 1.2 are as follows:

a) classification;
b) circuits and basic behaviour;
c) basic characteristics;
d) control scheme;
e) multiphase and multiple convertors;
f) analysis.

## 1.4 Convertor characteristics

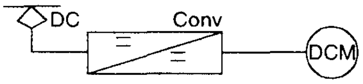
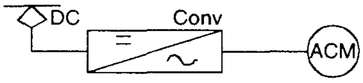
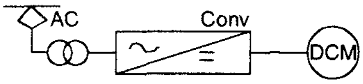
The convertor characteristics are either indicated in the data following the list below or calculated from the data in the figures and the explanations on how to calculate them. Multistage external commutated convertors are reduced to equivalent two-stage external commutated convertor models, and the characteristics are calculated from the two-stage models. Modelling of the stage reduction is explained in this specification.

Convertor characteristics are given in the following list:

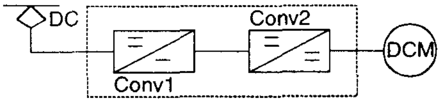
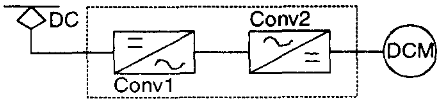
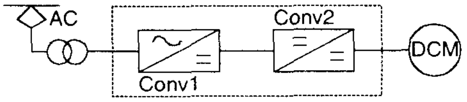
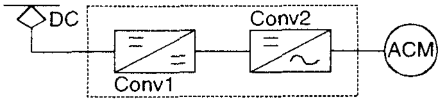
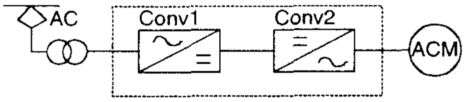
a) output characteristics of the convertors:
  1) average and/or r.m.s. voltage;
  2) average and/or r.m.s. current;
  3) voltage/current harmonics;
  4) voltage/current ripple;
b) input characteristics of the convertors:
  1) average and/or r.m.s. voltage;
  2) average and/or r.m.s. current;
  3) voltage/current harmonics;
  4) voltage/current ripple;
c) characteristics on the input side of power sources:
  1) average and/or r.m.s. current;
  2) current harmonics;
  3) current ripple;
  4) power factor (in the case of a.c. power sources);
d) characteristics on the input side of loads:
  1) average and/or r.m.s. voltage;
  2) average and/or r.m.s. current;
  3) current harmonics;
  4) current ripple;
  5) power factor (in the case of a.c. power sources).

The fundamental structures of the convertors, including convertor systems, are illustrated in tables 1 to 4.

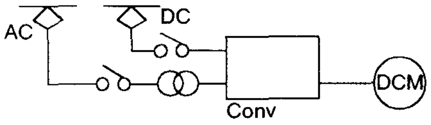
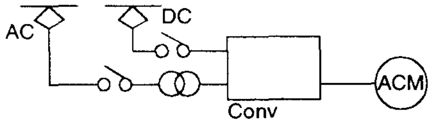
**Table 1 – Direct convertors for rolling stock**

| | | |
|---|---|---|
| No. 1 |  | Conv: Chopper |
| No. 2 |  | Conv: Inverter |
| No. 3 |  | Conv: Rectifier |

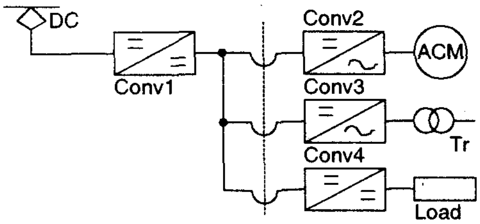
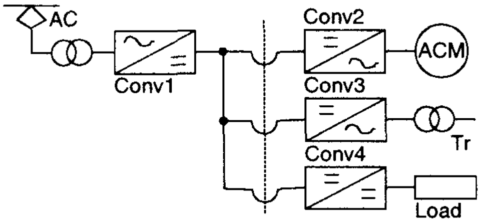
## Table 2 – Indirect convertors for rolling stock

| | | |
|---|---|---|
| No. 1 |  | Conv1: Chopper<br>Conv2: Chopper |
| No. 2 |  | Conv1: Inverter<br>Conv2: Rectifier |
| No. 3 |  | Conv1: Rectifier<br>Conv2: Chopper |
| No. 4 |  | Conv1: Chopper<br>Conv2: Inverter |
| No. 5 |  | Conv1: Rectifier<br>Conv2: Inverter |

## Table 3 – Convertors for multi-supply rolling stock

| | | |
|---|---|---|
| No. 1 |  | DC line<br>Conv: Chopper |
| | | AC line<br>Conv: Rectifier or indirect a.c./d.c. convertor |
| No. 2 |  | DC line<br>Conv: Inverter or indirect d.c./a.c. convertor |
| | | AC line<br>Conv: Indirect a.c./a.c. convertor |

## Table 4 – Convertor systems

| | | |
|---|---|---|
| No. 1 |  | Conv: Chopper<br>Conv: Inverter<br>Conv: Inverter<br>Conv: Chopper |
| No. 2 |  | Conv: Rectifier<br>Conv: Inverter<br>Conv: Inverter<br>Conv: Chopper |

## 2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 61287. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of IEC 61287 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 61287-1:1995, *Power convertors installed on board railway rolling stock – Part 1: Characteristics and test methods*

## 3 Direct convertors

### 3.1 External commutated rectifiers

### 3.1.1 General description

### 3.1.1.1 Basic connections

A convertor is composed of a single-bridge circuit, with two circuit connections: one where all the arms of the bridge are uniformly composed of either thyristors or diodes (uniform connection); the other where the arms are composed of both thyristors and diodes (non-uniform connection) (see figure 1).

### 3.1.1.2 Cascade connections

A convertor is composed of two or more bridges connected in series.

Where thyristors are used, the bridges are controlled stage by stage, sequentially (see figure 2).

### 3.1.1.3 Methods of phase control

The control methods for uniform connection are classified as symmetrical control and asymmetrical control. Non-uniform connections may be considered a special case of asymmetrical control.

### 3.1.1.4 Modes of operation

The characteristics of a rectifier circuit depend not only on the circuit connection and its phase control method but also on the operation mode.

There are many operation modes in a single-phase rectifier circuit using thyristors. Among these operation modes, only applications of practical use are considered in this specification.

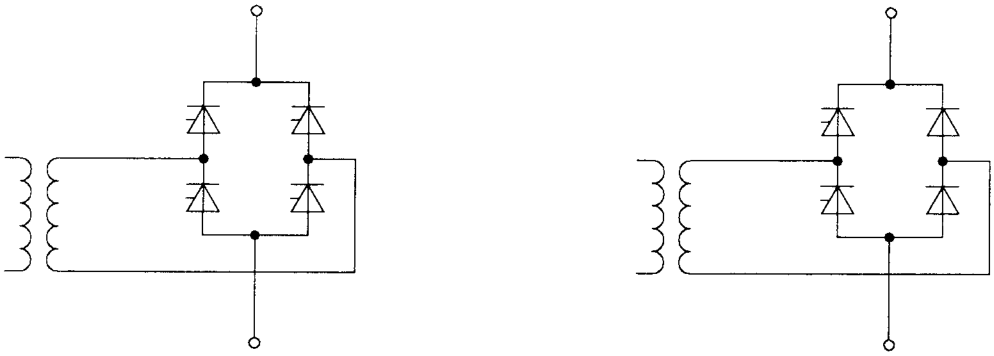


**Figure 1a – Uniform connection** **Figure 1b – Non-uniform connection**

**Figure 1 – Basic connections**

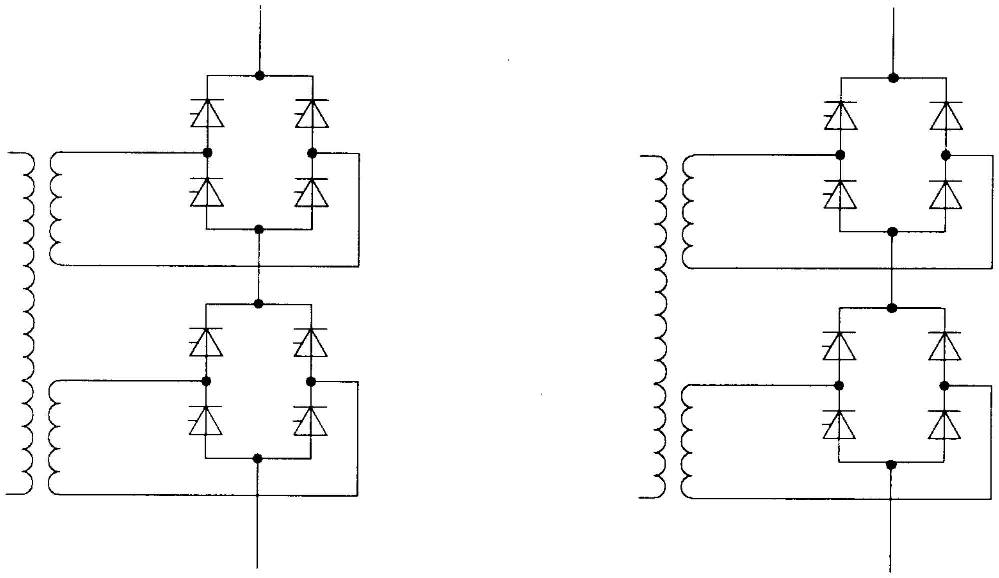


**Figure 2a – Uniform connection** **Figure 2b – Non-uniform connection**

**Figure 2 – Cascade connections**

The operation modes depend generally on the circuit connections, circuit constants and control angle, but, in some cases, they also depend on the control pulse width and the initial condition of the current. The basic operation mode for the rectifier circuit is that of a non-controlled bridge composed of diodes (see figure 3).

There are four kinds of basic operation modes, as follows:

a) mode I: this mode consists of a rectifying period and an off-state period, i.e. the d.c. side current flows intermittently;

b) mode II: in this mode the rectified current transfers direct from one pair of arms to the other, without the overlapping period;

c) mode III: this mode contains overlapping, rectifying and off-state periods within one half-cycle period, and the d.c. side current flows intermittently;

d) mode IV: this mode consists of an overlapping period and a rectifying period, and the d.c. side current flows continuously.

The above four modes are determined both by the ratio of d.c. electromotive force to a.c. source voltage and by the ratio of a.c. side reactance to d.c. side reactance. The ranges for these modes are shown in figure 4.

### 3.1.2 Classification of external commutated rectifiers

External commutated rectifiers are classified as shown in table 5.

**Table 5 – Classification of external commutated rectifiers**

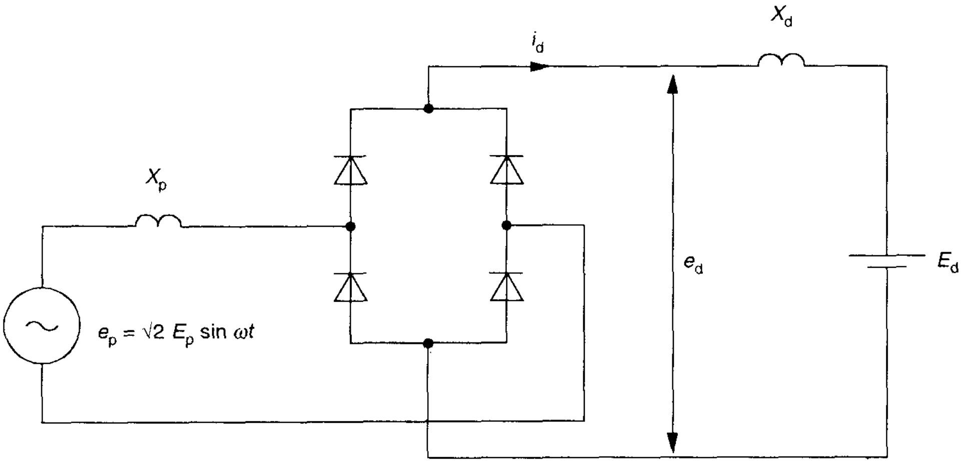
| **Number of stages** *n* | $n = 1$ | $n = 2$ | $n \geq 3$ |
|---|---|---|---|
| Uniform bridge | Diode bridge | Diode bridge | Diode bridge |
| | Thyristor bridge | Thyristor bridge | Thyristor bridge |
| Non-uniform bridge | Non-uniform bridge | Non-uniform bridge | Non-uniform bridge |

### 3.1.3 Characteristics in symmetrical control of a single-stage uniform bridge rectifier

The influence of resistive components in the single-phase rectifier circuit for electric rolling stock is practically negligible. If resistive components are neglected, the basic single-stage uniform convertor circuit is as shown schematically in figure 5. The principal characteristics of this circuit are shown in figures A.1 to A.6.

In these characteristics charts, the voltages and the currents are related to the a.c. source voltage $E_p$ and the a.c. side short-circuit current $E_p/X_p$ respectively. The forward voltage drops of the valves are neglected.

In figures A.1 to A.6, from a practical point of view, the related d.c. current $I_d \times X_p/E_p$ or control angle $\alpha$ is taken as the abscissa, and the control angle, impedance ratio $X_p/X_d$ or related d.c. current are chosen as parameters.



**Connections and supplies**

$e_p$: instantaneous value of a.c. source voltage

$E_p$: r.m.s. value of a.c. source voltage

$e_d$: instantaneous d.c. terminal voltage value of the diode bridge

$E_d$: d.c. electromotive force

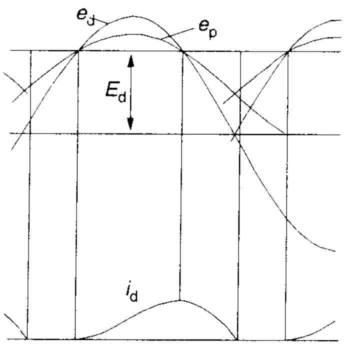
$i_d$: instantaneous value of d.c. side current

$X_p$: a.c. side reactance (commutating reactance)

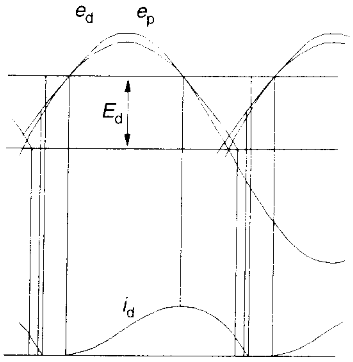
$X_d$: d.c. side reactance corresponding to a.c. source frequency.

**Figure 3 – Rectifier circuit to be considered**

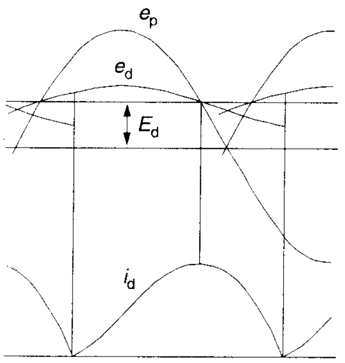
Mode I $\frac{X_p}{X_p + X_d} = 0,5$ $\frac{E_d}{\sqrt{2\,E_p}} = 0,7$



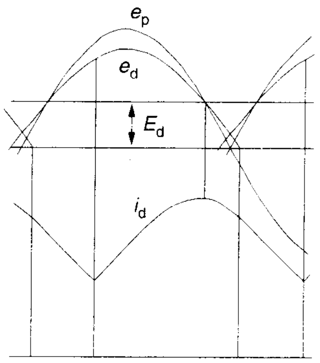
Mode III $\frac{X_p}{X_p + X_d} = 0,2$ $\frac{E_d}{\sqrt{2\,E_p}} = 0,63$



Mode II $\frac{X_p}{X_p + X_d} = 0,8$ $\frac{E_d}{\sqrt{2\,E_p}} = 0,4$



Mode IV $\frac{X_p}{X_p + X_d} = 0,3$ $\frac{E_d}{\sqrt{2\,E_p}} = 0,4$



Waveforms of rectifier output voltage and current

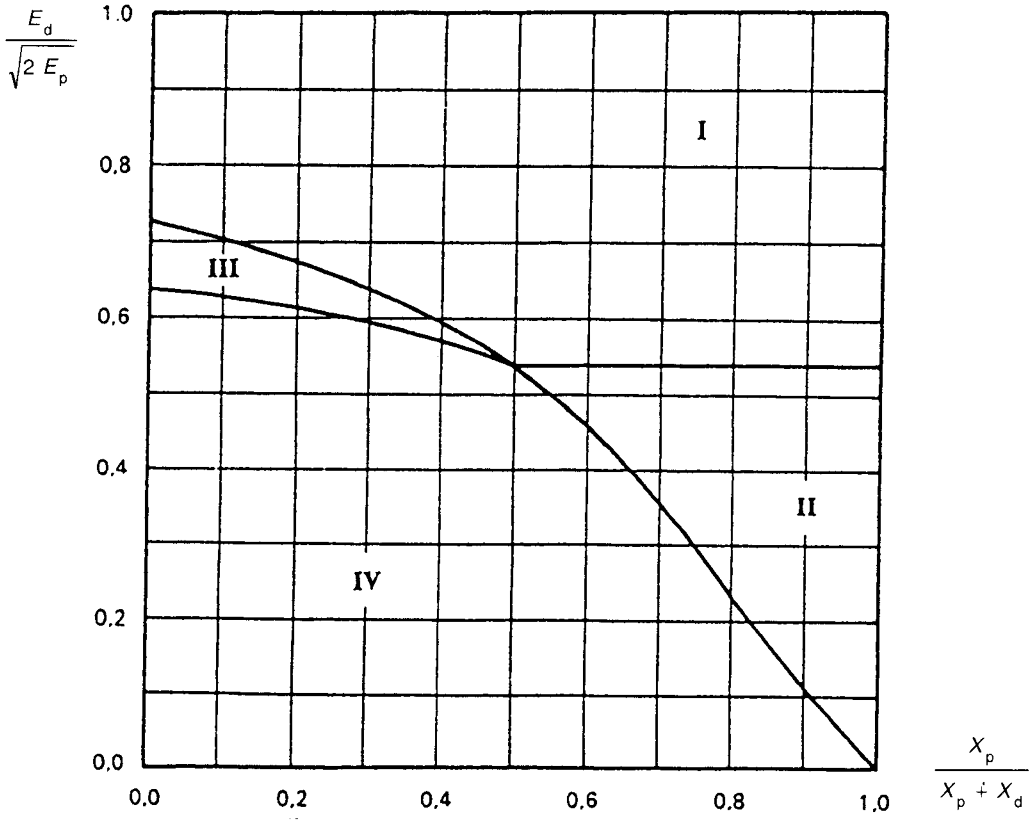
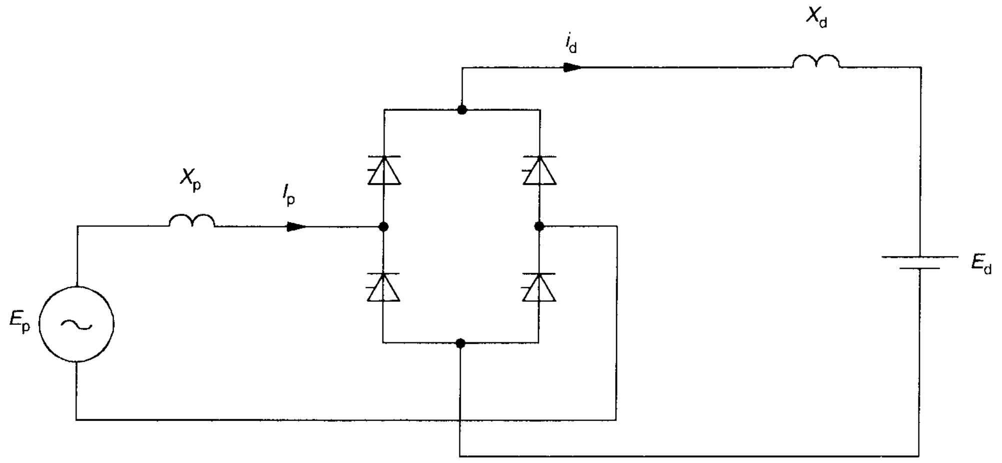


**Figure 4 – Ranges of operation modes**



**Connections and supplies**

$E_p$: r.m.s value of a.c. source voltage
$E_d$: d.c. electromotive force
$I_p$: r.m.s value of a.c. side current
$I_d$: mean value of d.c. side current
$I_c$: r.m.s value of d.c. side current
$X_p$: a.c. side reactance (commutating reactance)
$X_d$: d.c. side reactance corresponding to a.c. source frequency

NOTE This circuit is not always applicable to such loads as the pulsating-voltage motors whose terminal voltage varies appreciably according to the ripple current.

Figure 5 – Basic single-stage uniform bridge rectifier circuit

Symbols are shown as follows:

$\mu$: current ripple factor $\dfrac{I_{d\,max} - I_{d\,min}}{I_{d\,max} + I_{d\,min}}$

$\lambda$: total power factor (negative value means inverter operation)

cos $\varphi$: displacement factor (negative value means inverter operation)

$$J_p = \frac{\sqrt{\sum (S_n \times I_n)^2}}{\sqrt{\sum I_n{}^2}} \times 100 \text{ A}$$

where

$I_n$ is the $n$th harmonic current, in amperes;

$S_n$ is the telephone interference factor.

It is assumed that the control pulse has a suitable length.

Operation mode boundaries are shown as follows:

............. critical line of effective control
—•—•—• critical line of commutation failure
------------ boundary between continuous mode and intermittent mode

### 3.1.4 Characteristics of single-stage non-uniform bridge rectifiers

There are several kinds of arm connections in a non-uniform bridge rectifier. Of these connections, the a.c. side symmetrical connection is the most popular (see figure 1). However, the characteristics expressed in these charts are commonly applicable to other connections.

The principal characteristics of this non-uniform convertor are shown in figures A.7 to A.11. In these characteristics charts, the resistive components are neglected and the control pulse is assumed to have a suitable length. Symbols and parameters are the same as those on charts of a uniform convertor.

Operation mode boundaries are shown as follows:

| | |
|---|---|
| .............. | critical line of effective control |
| ------------- | boundary between continuous mode and intermittent mode |

### 3.1.5 Characteristics of a two-stage rectifier

### 3.1.5.1 Model circuit

The characteristics of the following two-stage cascade connection (see figure 6), in which the turns ratio of the two secondary windings of the main transformer is different, are the same as those of the general multi-stage cascade connection.

The symbols used are as follows:

| | |
|---|---|
| $E_p$ | r.m.s. value of a.c. line side voltage |
| $E_{p1}$, $E_{p2}$ | r.m.s. value of a.c. valve side voltage<br>$E_{p1} + E_{p2} = E_p$<br>$a_1 = E_{p1}/E_p$, $a_2 = E_{p2}/E_p$ $(a_1 + a_2 = 1)$ |
| $E_d$ | d.c. electromotive force |
| $I_p$ | r.m.s. value of a.c line side current |
| $I_{p1}$, $I_{p2}$ | r.m.s. value of a.c. valve side current |
| $I_d$ | mean value of d.c. side current |
| $X_{p1}$, $X_{p2}$ | a.c. side reactance (commutating reactance) |
| $X_p$ | a.c. side reactance of the total winding<br>$X_{p1} + X_{p2} = X_p$<br>$X_{p1} = a_1\ X_p$, $X_{p2} = a_2\ X_p$ |
| $X_d$ | d.c. side reactance corresponding to a.c. line frequency |
| $\alpha_1$ | the control angle of the $\alpha_1$ winding side bridge $\alpha_1$ |
| $\alpha_2$ | the control angle of the $\alpha_2$ winding side bridge $\alpha_2$ |
| $K$ | the ratio of a.c. side reactance and d.c. side reactance ($K = X_p/X_d$) |

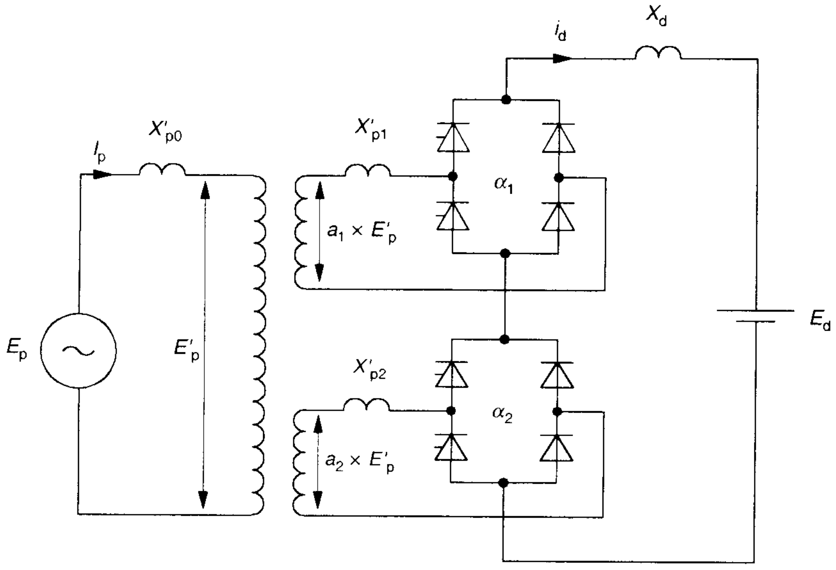
### 3.1.5.2 Calculation method

The following are examples of the approximate method of calculation of characteristics for a cascade connection:

where

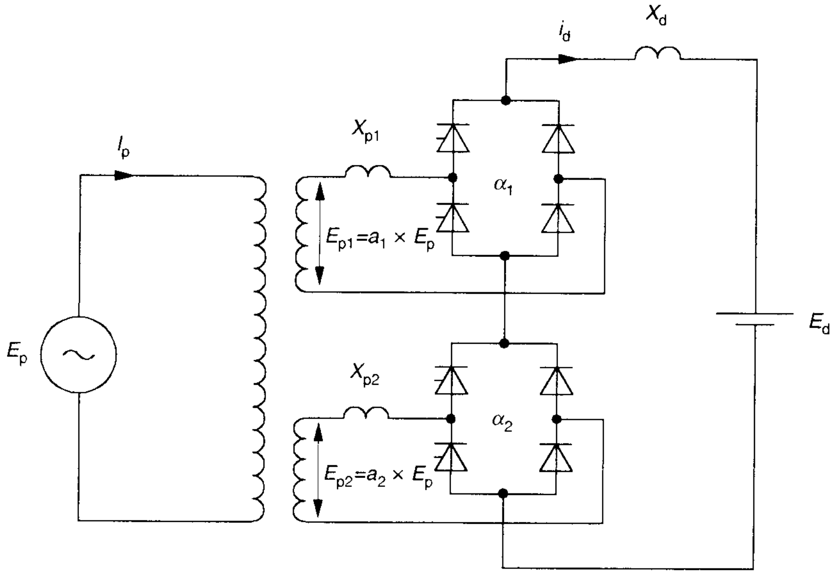
| | |
|---|---|
| $()\ \alpha_1$ | represents the characteristics of the single-stage connection for the control angle $\alpha_1$ with $K$; |
| $()\ \alpha_1$ | represents the characteristics of the single-stage connection for the control angle $\alpha_2$ with $K$; |
| $()\ \alpha_1\ \alpha_2$ | represent the characteristics of the cascade connection, in which one bridge corresponding to $a_1$ winding has control angle $\alpha_1$, and the other bridge corresponding to $a_2$ winding has control angle $\alpha_2$. |

where $K$ is equal to the value corresponding to the cascade connection ($K = X_p/X_d$).



$(a_1 + a_2 = 1)$

Figure 6a – Model circuit



$$X_{p1} = X'_{p1} + a_1 X'_{p0}$$
$$X_{p2} = X'_{p2} + a_2 X'_{p0}$$
$$a_1 + a_2 = 1$$

Figure 6b – Practically equivalent circuit

Figure 6 – Model for general multi-stage cascade connection

#### 3.1.5.2.1 DC voltage regulation

$$\left(\frac{E_d}{E_p}\right)_{\alpha_1\ \alpha_2} = a_1\left(\frac{E_d}{E_p}\right)_{\alpha_1} + a_2\left(\frac{E_d}{E_p}\right)_{\alpha_2}$$

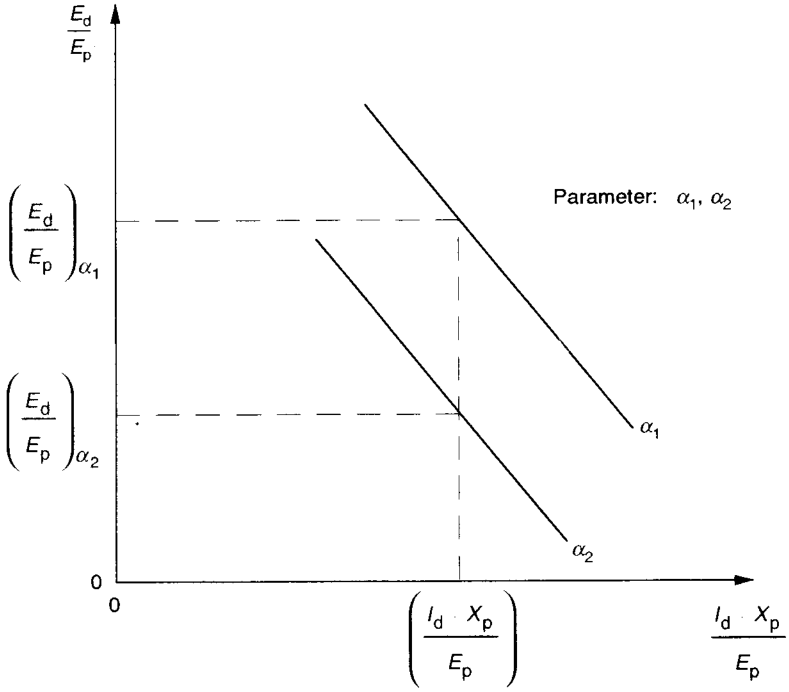


**Figure 7 – DC voltage regulation** (see figure A.7)

### 3.1.5.2.2 AC line side current

$$\left(\frac{I_p}{I_d}\right)_{\alpha_1\,\alpha_2} = \left| a_1 \left(\frac{I_p}{I_d}\right)_{\alpha_1} \left(\cos\varphi_{\alpha_1} - j\cdot\sin\varphi_{\alpha_1}\right) + a_2 \left(\frac{I_p}{I_d}\right)_{\alpha_2} \left(\cos\varphi_{\alpha_2} - j\cdot\sin\varphi_{\alpha_2}\right) \right|$$

$\varphi_{\alpha_1} = \cos^{-1} (\cos\varphi)_{\alpha_1}$ (see figure 10)

$\varphi_{\alpha_2} = \cos^{-1} (\cos\varphi)_{\alpha_2}$ (see figure 10)

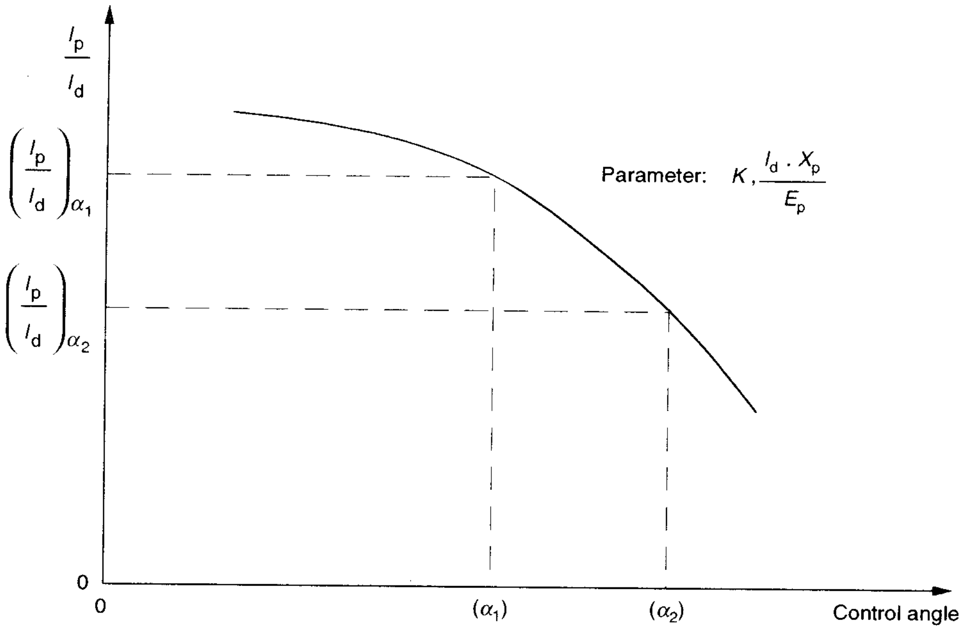


**Figure 8 – AC line side current** (see figure A.11)

### 3.1.5.2.3 Total power factor

$$(\lambda)_{\alpha_1\alpha_2} = \left\{ a_1 \, \lambda_{\alpha_1} \left( \frac{I_p}{I_d} \right)_{\alpha_1} + a_2 \, \lambda_{\alpha_2} \left( \frac{I_p}{I_d} \right)_{\alpha_2} \right\} \frac{1}{\left( \frac{I_p}{I_d} \right)_{\alpha_1\alpha_2}}$$

$$\lambda_{\alpha_1} = (\lambda)_{\alpha_1}, \; \lambda_{\alpha_2} = (\lambda)_{\alpha_2}$$

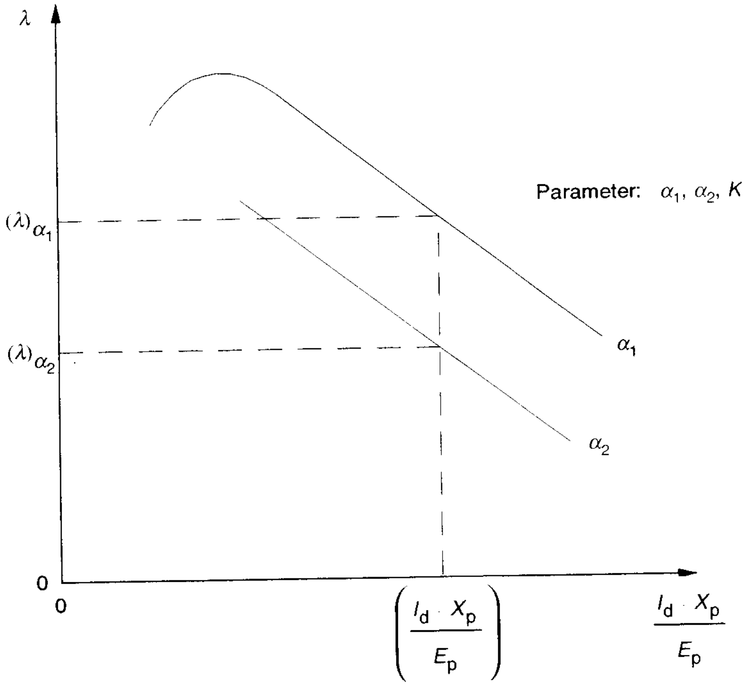


**Figure 9 – Total power factor** (see figure A.9)

### 3.1.5.2.4 Displacement factor

$$(\cos\varphi)_{\alpha_1\alpha_2} = \cos\left\{\tan^{-1}\frac{a_1\left(\frac{I_p}{I_d}\right)_{\alpha_1}\sin\varphi_{\alpha_1} + a_2\left(\frac{I_p}{I_d}\right)_{\alpha_2}\sin\varphi_{\alpha_2}}{a_1\left(\frac{I_p}{I_d}\right)_{\alpha_1}\cos\varphi_{\alpha_1} + a_2\left(\frac{I_p}{I_d}\right)_{\alpha_2}\cos\varphi_{\alpha_2}}\right\}$$

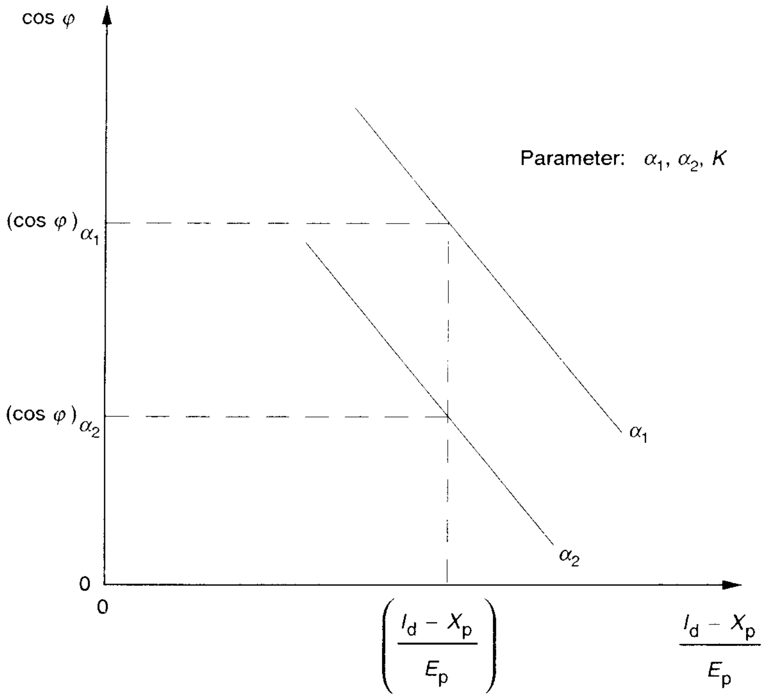


**Figure 10 – Displacement factor** (see figure A.10)

### 3.1.6 Characteristics of multi-stage rectifiers

The characteristics of the single-stage and two-stage rectifiers can be calculated direct from the formulae. The characteristics charts in this report have been drawn from the formulae. This calculation method is, however, impossible for rectifiers with more than two stages. The following two calculation techniques are applied in this case.

a) Equivalent two-stage technique

The rectifier characteristics are calculated from an equivalent two-stage model through a transformation of the circuit configuration. This method allows for an accurate calculation of the characteristics of the effective value of the fundamental wave. On the other hand, the accuracy of the characteristics of harmonics is not precise, since interactions among transformer windings when commutation occurs are neglected.

b) Simulation

The original circuit is analysed with simulation software: software for the analysis is essential.

Analysis of a multi-stage rectifier (with no more than two stages) is explained by using the equivalent two-stage model.

### 3.1.7 Transformation of a multi-stage rectifier to an equivalent two-stage model

The stage of the rectifier unit of the multi-stage rectifier is identified from one of the following three types:

a) full voltage;

b) controlled voltage;

c) by-pass (see figure 11).

In this case, the rectifier units of the by-pass stage are neglected.

#### 3.1.7.1 Method of transformation of the multi-stage rectifier with same control angle to an equivalent single-stage model

a) Rectifier units whose phase-angle controls are over (full-voltage stage)

   1) Multi-stage rectifiers, whose phase-angle controls are over, are transformed to an equivalent secondary circuit (see figure 12).

   2) Multi-stage rectifiers modified to the equivalent secondary circuit, are transformed to single-stage rectifier (see figure 13).

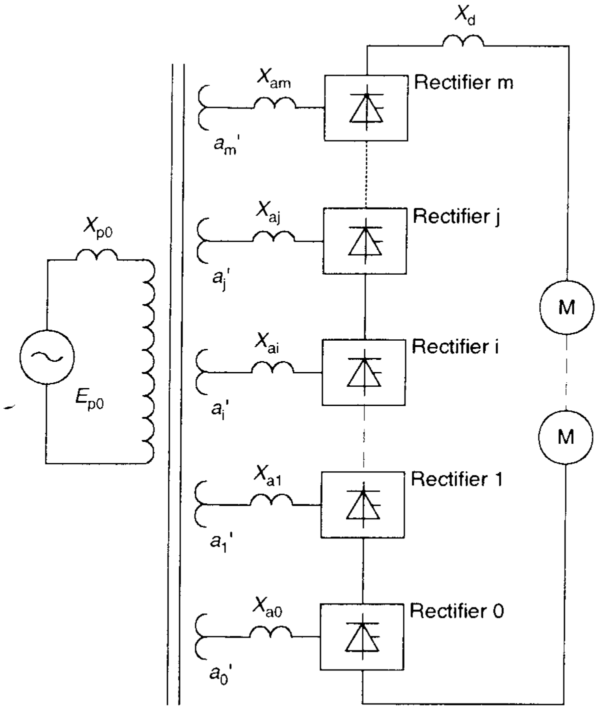
b) Rectifier units, controlled with the same control phase angle (controlled-voltage stage)

   1) Multi-stage rectifiers, which are controlled with the same control phase angle, are transformed to an equivalent secondary circuit (see figure 14).

   2) Multi-stage rectifiers, transformed to the equivalent secondary circuit, are transformed to single-stage rectifiers (see figure 15).

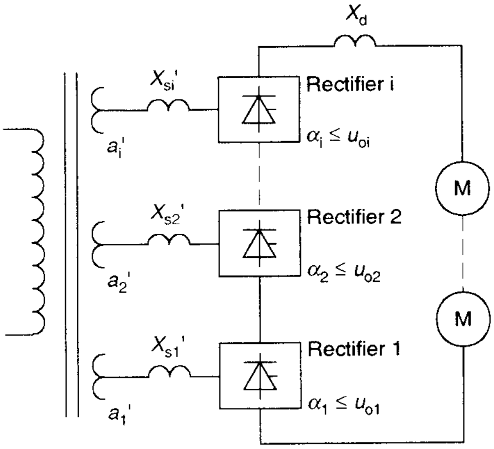
### 3.1.7.2 Method of transformation of the multi-stage rectifier to an equivalent two-stage model

The equivalent single-stage rectifier whose phase-angle control is over, and the equivalent single-stage rectifier which is phase-controlled are transformed to an equivalent two-stage model (see figure 16).



Rectifier 0: by-pass stage rectifier unit
Rectifier 1~Rectifier i: full-voltage stage rectifier unit
Rectifier j~Rectifier m: controlled voltage stage rectifier unit
$a_0'$, $a_1'$ ~ $a_m'$: turn ratio (number of secondary windings/number of primary windings)
$X_{po}$: reactance of primary winding and a.c. line
$X_{a0}$, $X_{a1}$ ~ $X_{am}$: reactance of secondary winding
$X_d$: d.c. side reactance corresponding to a.c.
$E_{p0}$: a.c. source voltage

**Figure 11 – Multi-stage rectifier (m-stage cascade rectifier)**

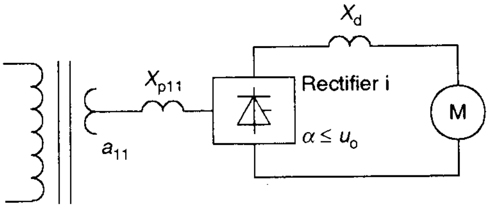


$X_{s1}'$ ~ $X_{si}'$ equivalent reactance modified to secondary circuit

$u_{o1}$ ~ $u_{oi}$ equivalent angle of overlap

$$X_{s1}' = a_1' X_{po} + X_{si}$$
$$X_{s2}' = a_2' X_{po} + X_{s2}$$
$$X_{si}' = a_i' X_{po} + X_{si}$$

**Figure 12 – Equivalent secondary circuit for cascade rectifier (full-voltage stage)**



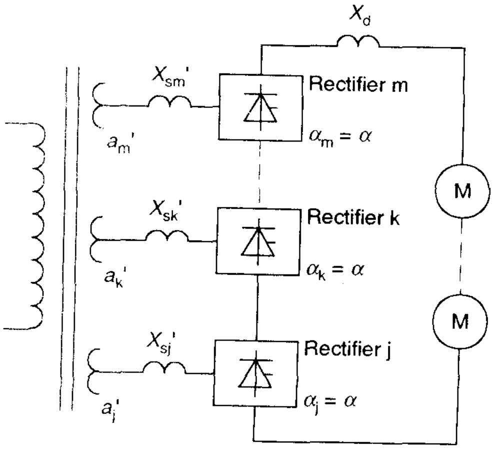
$X_{p11}$ equivalent reactance modified to a single-stage rectifier

$a_{11}$ equivalent turn ratio modified to a single-stage rectifier

$u_1$ equivalent angle of overlap modified to a single-stage rectifier

$$X_{p11} = X_{p1}' + X_{p2}' + \ldots + X_{pm}'$$
$$a_{11} = a_1' + a_2' + \ldots + a_m'$$

**Figure 13 – Equivalent single-stage rectifier for cascade rectifier (full-voltage stage)**



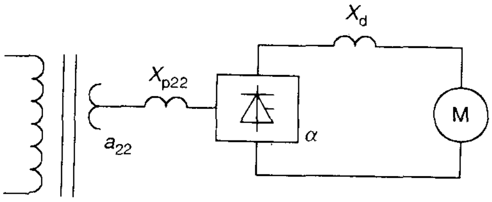
| | |
|---|---|
| $X_{sj}' \sim X_{sm}'$ | equivalent reactance modified to secondary circuit |
| $\alpha_j \sim \alpha_m$ | control angle (same angle) |

$$X_{sj}' = a_1' X_{po} + X_{si}$$

$$X_{pk}' = a_k' X_{po} + X_{s2}$$

$$X_{pm}' = a_m' X_{po} + X_{sm}$$

**Figure 14 – Equivalent secondary circuit for cascade rectifier (controlled-voltage stage)**

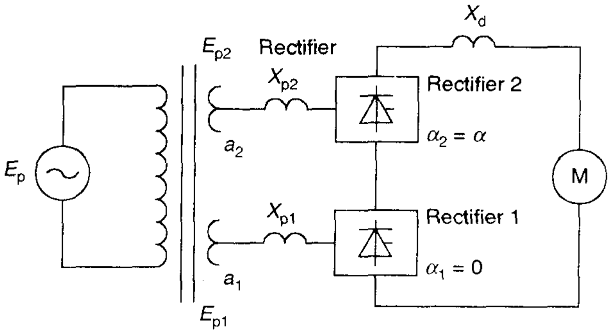


| | |
|---|---|
| $X_{p22}$ | equivalent reactance modified to a single-stage rectifier |
| $a_{22}$ | equivalent turn ratio modified to a single-stage rectifier |
| $\alpha$ | control angle |

$$X_{p22} = X_{sj}' + X_{sk}' + \ldots + X_{sm}'$$

$$a_{22} = a_j' + a_k' + \ldots + a_m'$$

**Figure 15 – Equivalent single-stage rectifier for cascade rectifier (controlled-voltage stage)**



| | |
|---|---|
| Rectifier 1: | full-voltage stage |
| Rectifier 2: | controlled-voltage stage |
| $a_1$, $a_2$ | equivalent turn ratio modified to an equivalent two-stage model |
| $X_{p1}$, $X_{p2}$ | equivalent reactance modified to an equivalent two-stage model |
| $E_{p1}$, $E_{p2}$ | equivalent a.c. valve side voltage modified to an equivalent two-stage model |

$$a_1 = a_{11}/(a_{11} + a_{22})$$
$$a_2 = a_{22}/(a_{11} + a_{22})$$
$$(a_1 + a_2 = 1)$$
$$E_p = E_{po}\ (a_{11} + a_{22})$$
$$E_{p1} = E_p \times a_1$$
$$E_{p2} = E_p \times a_2$$
$$(E_{p1} + E_{p2} = E_p)$$

**Figure 16 – Equivalent two-stage model**

### 3.1.7.3 Calculation accuracy

One cannot expect great accuracy in calculating characteristics concerning harmonics in the method of the equivalent two-stage model, since mutual inductions among transformer windings are based on a simplified assumption. The relationship between characteristic items and accuracy is summarized in table 6.

**Table 6 – Accuracy of the calculation by the equivalent two-stage model**

| Characteristic item | Accuracy |
|---|---|
| Average output voltage | A [a] |
| Average output current | A |
| Output current ripple | A |
| Effective value of input current | A |
| Displacement factor | A |
| Total power factor | B [b] |
| Input harmonic current | C [c] |
| Jp: Psophometric current | C |
| Distortion of input voltage | C |

[a] A: good (acceptable as an approximation).
[b] B: not good (still acceptable as an approximation).
[c] C: bad (not acceptable).

### 3.2 Self-commutated rectifiers

#### 3.2.1 Classification of self-commutated rectifiers

Self-commutated rectifiers are classified according to the following categories:

a) number of phases – single-phase/multiphase;
b) type of power sources – voltage-stiff/current-stiff;
c) structure – full bridge/half bridge;
d) control – pulse-width modulation (PWM) control/square-wave control.

The classification is summarized in table 7.

**Table 7 – Classification of the self-commutated rectifiers**

| Classification | Name | | Definition |
|---|---|---|---|
| Number of phases | Single-phase rectifiers | | Single-phase self-commutated rectifier |
| | Multiphase rectifiers | | Multiphase self-commutated rectifier |
| Power source | Voltage-stiff rectifiers | | Self-commutated rectifier with capacitor on the d.c. side operated as a voltage source |
| | Current-stiff rectifiers | | Self-commutated rectifier with reactor on the d.c. side operated as a current source |
| Structure | Full-bridge rectifiers | | Self-commutated rectifier, all arms of which consist of switching devices |
| | Half-bridge rectifiers | I-type | Self-commutated rectifier, one d.c. terminal of which is connected to rectifier arms, and the other terminal of which is connected to the neutral point of the a.c. power source |
| | | V-type | Self-commutated rectifier, one a.c. terminal of which is connected to the middle point of rectifier arms, and the other terminal of which is connected to the middle point of the d.c. load. |
| Control | PWM-control rectifiers | | Self-commutated rectifier whose a.c. voltage/current is controlled with pulse width modulation |
| | Square-wave rectifiers | | Self-commutated rectifier whose a.c. voltage/current is a square wave in a half-period |

The self-commutated rectifiers of single-phase, voltage-stiff, full bridge and PWM-control are commonly used and are described in 3.2.2 and 3.2.3.

#### 3.2.2 Single-stage, self-commutated rectifiers

##### 3.2.2.1 Basic circuit

The basic circuit and behaviour are illustrated in figure 17.

##### 3.2.2.2 Typical waveform

A typical waveform of a self-commutated rectifier is shown in figure 18.

##### 3.2.2.3 Basic behaviour

a) Input side (a.c. side) of the rectifier
   1) The voltage waveform consists of a pulse train, whose fundamental wave has the same frequency as the a.c. power source.
   2) The current harmonic which flows in the power source side is determined by the voltage harmonics and the impedance on the a.c. side.

b) Output side (d.c. side) of the rectifier
   1) The current contains many harmonics whose fundamental frequency is twice the frequency of the a.c. power source.
   2) The a.c. components of the current on the output side are mainly absorbed by a smoothing capacitor.
   3) The voltage ripple on the output side is determined by the a.c. components in the output current and the capacity of the smoothing capacitor.

#### 3.2.2.4 Control

The control principle of voltage waveform generation is the same as the voltage-stiff inverter (see 3.4.4).

The output voltage value is controlled by changing the amplitude and phase of the PWM-controlled fundamental voltage ( $V_{a.c.}$ in figure 17) compared with the line voltage.

#### 3.2.2.5 Characteristics

The basic characteristics are the same as those of the voltage-stiff inverter (see 3.4.6).

### 3.2.3 Multiple, self-commutated rectifiers

#### 3.2.3.1 Configurations

Several units of voltage-stiff self-commutated rectifiers are connected in series or parallel to the load side.

Typical configurations are illustrated in figure 19.

#### 3.2.3.2 Multiphase operation

Each unit rectifier is operated on the basis of different PWM-waveform signals with various phase angles in the multiple convertor.

The multiphase operations can reduce the harmonics in the a.c. side current.

### 3.2.4 Current-stiff self-commutated rectifiers

Current-stiff self-commutated rectifiers are used in some cases. Basic configurations are shown in figure 20.

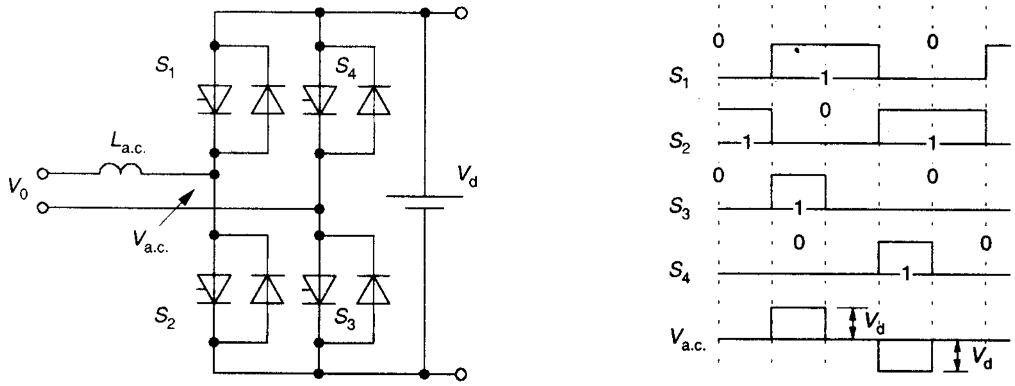


**Figure 17 – Single-phase self-commutated rectifier (full bridge type)**

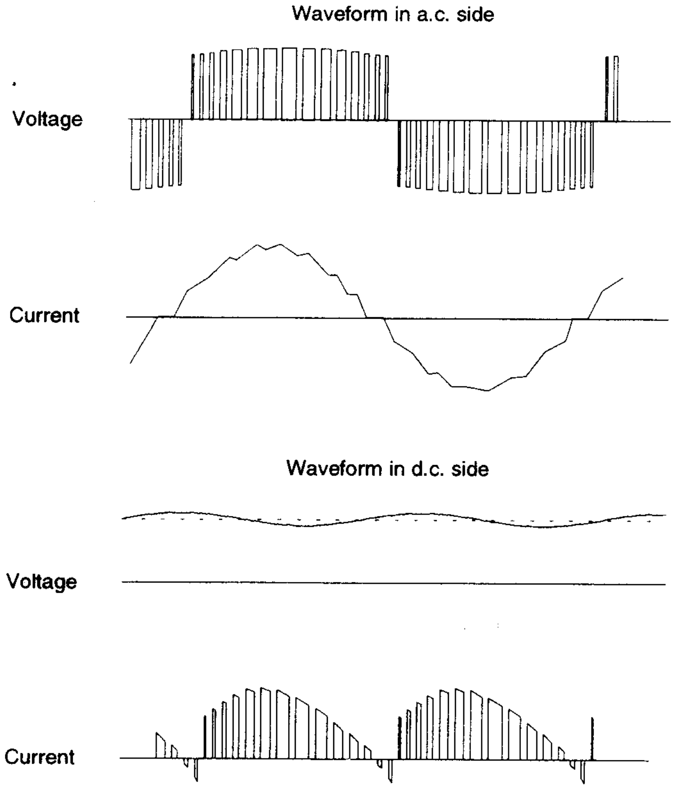


**Figure 18 – Typical waveform of the self-commutated rectifier**

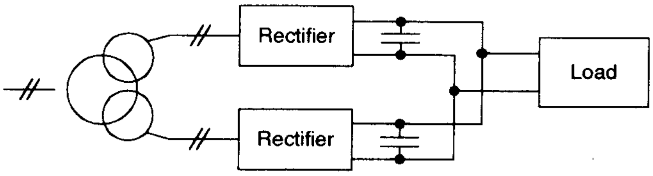
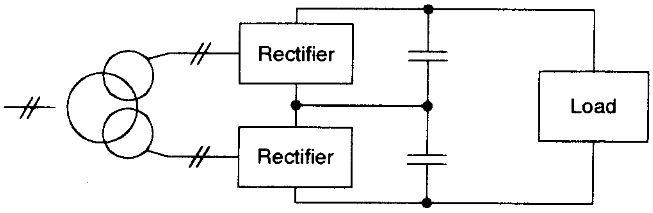
| Type of multiple | Basic configurations of system |
|---|---|
| Parallel type |  |
| Series type |  |

**Figure 19 – Voltage-stiff multiple self-commutated rectifiers**

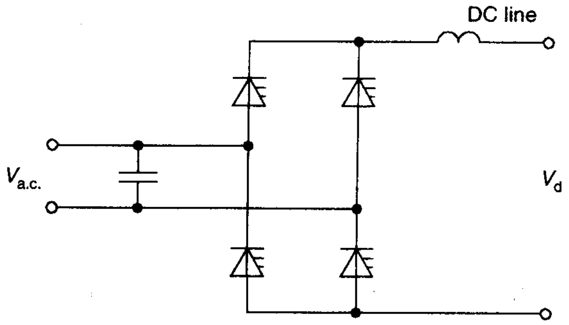


**Figure 20 – Basic configuration of current-stiff self-commutated rectifier**

## 3.3 Choppers

### 3.3.1 Classification of choppers

The choppers described are classified below.

a) Unidirectional choppers
  - step-up choppers, step-down choppers;
  - step-up-and-down choppers.

b) Bi-directional choppers
  - two-quadrant voltage choppers, two-quadrant current choppers;
  - four-quadrant choppers.

Basic circuit configurations are summmarized in table 8.

The description here is limited to choppers that have both input and output terminals. Other choppers, for example, resistance choppers as illustrated in figure 21, are excluded.

Operation of all the choppers listed above can be explained as a combination of the fundamental operations of step-up and step-down choppers. These two types of chopper are described in the following subclauses.

### 3.3.2 Step-down choppers

#### 3.3.2.1 Basic circuit configuration

The basic circuit of a step-down chopper is shown in figure 22.

#### 3.3.2.2 Basic waveform

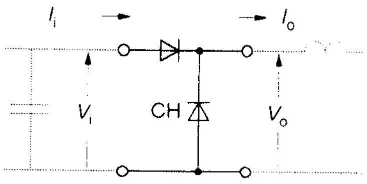
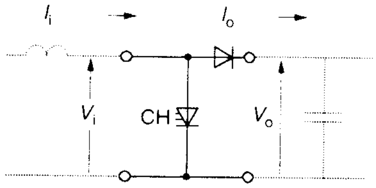
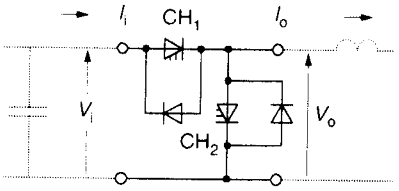
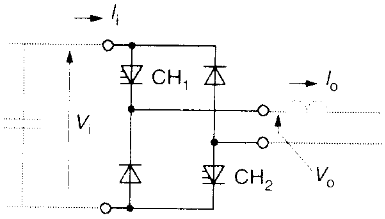
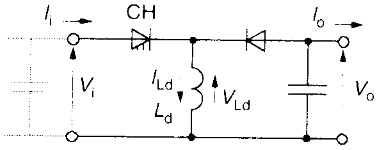
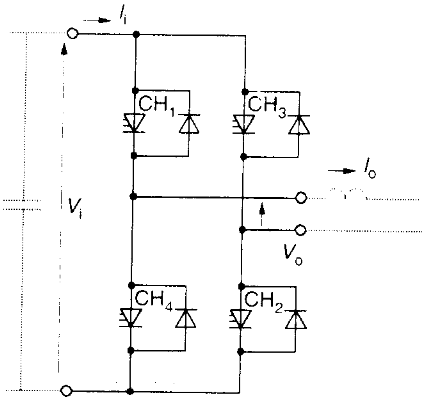
The basic waveform of a step-down chopper is shown in figure 23.

#### 3.3.2.3 Basic behaviour

a) Output side of the chopper
  1) The output voltage consists of pulses whose peak voltage is the same as the input voltage.
  2) The output voltage contains harmonics whose fundamental frequency is the same as the chopping frequency.
  3) The output current is a d.c. current with a ripple, which is determined by the harmonics of the output voltage and the reactance on the output side, i.e. the summation of the reactances of the smoothing reactor and the load.

b) Input side of the chopper
  1) The input current consists of pulses whose peak current is the same as the output current.
  2) The input current contains harmonics whose fundamental frequency is the same as the chopping frequency.
  3) The harmonic current flows through the filter into the power source.
  4) The harmonic currents in the source are decreased to the extent determined by the characteristics of the filter.

## Table 8 – Basic circuit configuration of choppers

| Chopper | Basic circuit configuration |
|---|---|
| Step-down |  |
| Step-up |  |
| Current-stiff two-quadrant |  |
| Voltage-stiff two-quadrants |  |
| Step-down/up |  $I_i$<br>CH<br>$I_o$<br>$V_i$<br>$I_{Ld}$<br>$L_d$<br>$V_{Ld}$<br>$V_o$ |
| Four-quadrant |  $I_i$<br>$CH_1$<br>$CH_3$<br>$I_o$<br>$V_i$<br>$V_o$<br>$CH_4$<br>$CH_2$ |

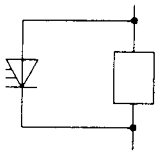
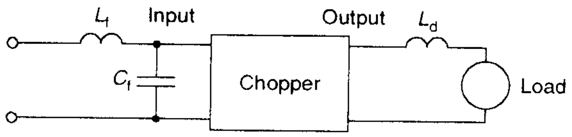


Figure 21 – Resistance chopper



$L_f$: input filter reactor

$C_f$: input filter capacitor

$L_d$: smoothing reactor

Figure 22 – Basic circuit of a step-down chopper

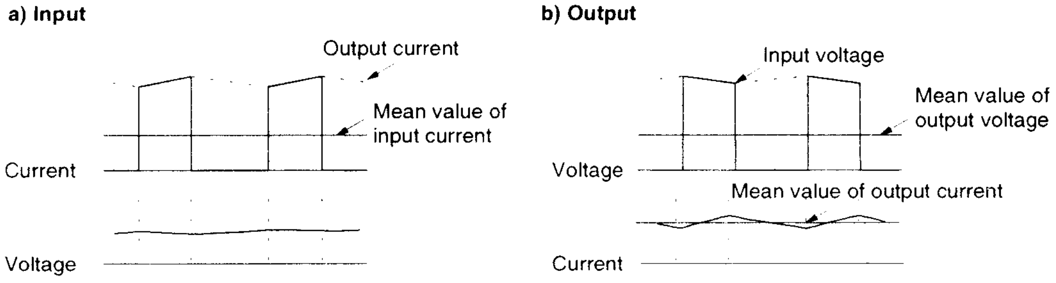

a) Input
Output current
Mean value of input current
Current
Voltage
b) Output
Input voltage
Mean value of output voltage
Voltage
Mean value of output current
Current

**Figure 23 – Basic waveform of a step-down chopper**

### 3.3.2.4 Output voltage

The output voltage $V_o$ is proportional to the conduction ratio $\alpha$.

$$V_o = \alpha \times V_i \tag{1}$$

$$\alpha = \frac{T_{on}}{T} \tag{2}$$

where

$V_i$ is the average input voltage, in volts;

$T_{on}$ is the conduction interval;

$T$ is the period of the chopper.

### 3.3.2.5 Output current ripple

The output current ripple $\Delta I_o$ is a function of the conduction ratio $\alpha$ as shown in figure 24.

$$\Delta I_o = \frac{V_i}{L_o} T \alpha (1-\alpha) \tag{3}$$

where

the resistance in the circuit is neglected;

$L_o$ is the inductance in the output side.

### 3.3.3 Step-up choppers

### 3.3.3.1 Basic circuit configuration

The basic circuit of a step-up chopper is shown in figure 25.

### 3.3.3.2 Basic waveform

Basic waveform of a step-up chopper are shown in figure 26.

#### 3.3.3.3 Basic behaviour

a) Output side of the chopper

   1) The output current consists of pulses whose peak current is the same as the input current.

   2) The output current contains harmonics whose fundamental frequency is the same as the chopping frequency.

   3) The output voltage is d.c. voltage with ripple, which is determined by the harmonics of the output current and the filter capacitor on the output side.

b) Input side of the chopper

   1) The input voltage consists of pulses whose peak voltage is the same as the output voltage.

   2) The input voltage contains harmonics whose fundamental frequency is the same as the chopping frequency.

   3) The input current is the direct current containing ripples; these ripple harmonics are determined by the input-voltage harmonics and the inductance on the input side, i.e., the sum of the inductances of the smoothing reactor and the source.

#### 3.3.3.4 Output voltage

The ratio of the output voltage $V_o$ to the input voltage $V_i$ is in reverse ratio to $1 - \alpha$ and is given by the following equation:

$$\frac{V_o}{V_i} = \frac{1}{1-\alpha}$$

where $\alpha$ is the conduction ratio of the chopping part.

#### 3.3.3.5 Input current ripple

The input current ripple $\Delta I_i$ is expressed as the following formula:

$$\Delta I_i = \frac{V_o}{L_i} T \alpha (1-\alpha) \qquad (4)$$

where

the resistance in the circuit is neglected;

$L_i$ is the inductance on the input side.

### 3.3.4 Basic control scheme

As explained in 2.2.3.4 of IEC 61287-1, there are three methods to control a chopper and obtain a variable d.c. output voltage:

- a variable pulse-width with a fixed frequency;
- a fixed pulse-width with a variable frequency;
- a combination of these two methods.

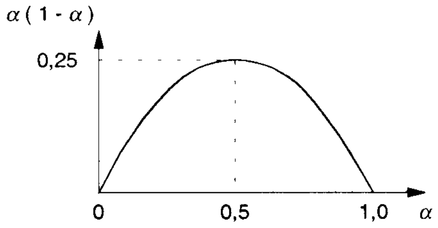
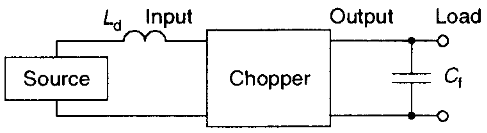


**Figure 24 – Coefficient of output current ripple**



$L_d$: somce inductance

$C_f$: filter capacitor

**Figure 25 – Basic circuit of a step-up chopper**

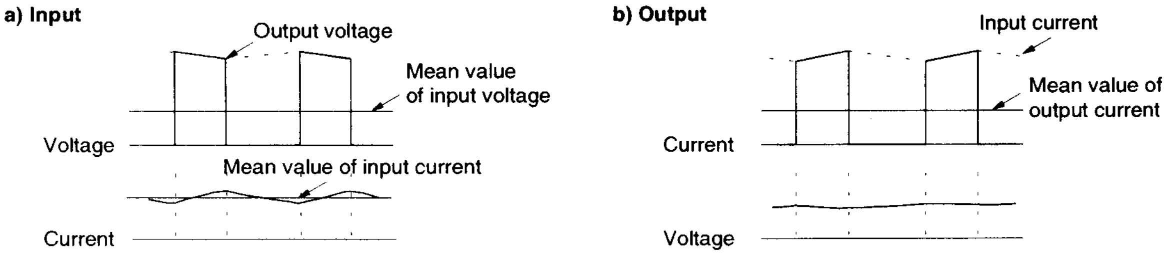
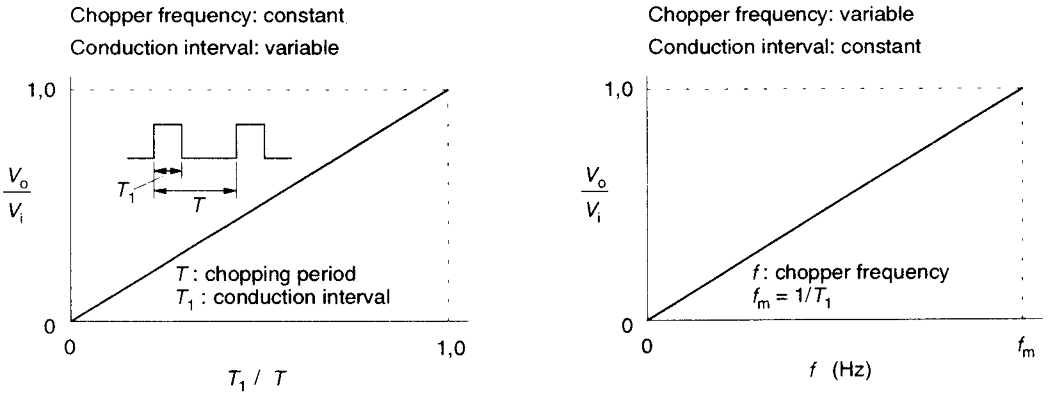


**Figure 26 – Basic waveform of a step-up chopper**


Chopper frequency: constant
Conduction interval: variable

Chopper frequency: variable
Conduction interval: constant

**Figure 27 – Basic characteristic curves under the control of a step-down chopper**

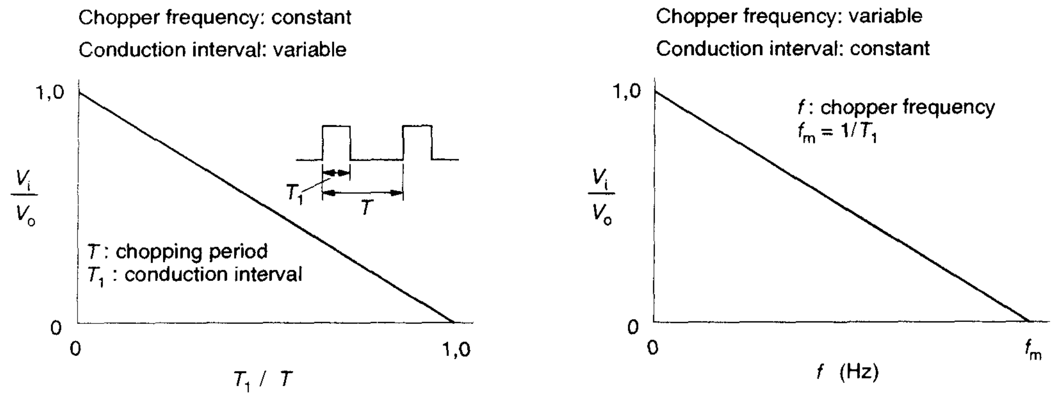


Figure 28 – Basic characteristic curves under the control of a step-up chopper

### 3.3.4.1 Step-down chopper

The characteristic curves under the control of a step-down chopper are illustrated in figure 27.

### 3.3.4.2 Step-up chopper

The characteristic curves under the control of a step-up chopper are illustrated in figure 28.

### 3.3.4.3 Variable frequency and variable conduction interval control

The instant value of the current/voltage is controlled by adjusting both the chopping frequency and the conduction interval simultaneously.

### 3.3.5 Multiphase and/or multiple choppers

### 3.3.5.1 Definition

a) Multiphase chopper

A chopper which has two or more chopping parts synchronized, phase-delayed and connected to the same power supply system.

b) Multiple chopper

A chopper which has two or more chopping parts synchronized, phase-delayed and connected to the same load.

Basic circuit configurations of multiphase and multiple choppers are shown in figure 29.

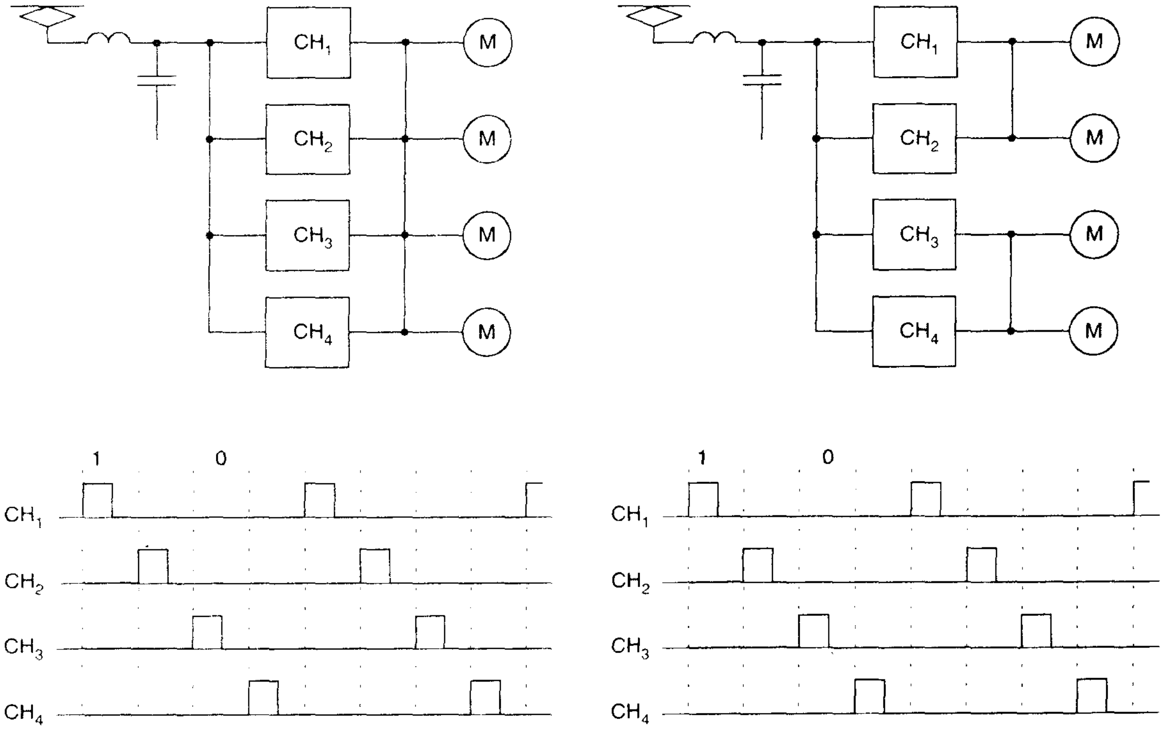


**Figure 29a – Four-phase, four-multiple chopper**

**Figure 29b – Four-phase, two-multiple chopper**

**Figure 29 – Basic circuit configurations of a multiphase and multiple chopper**

### 3.3.5.2 Purpose

The main advantage of a multiphase chopper is to reduce the harmonic contents on the input side.

The main advantage of a multiple chopper is to reduce the harmonic contents of output ripple.

### 3.3.6 Electric characteristics

### 3.3.6.1 Step-down chopper

Only a single-phase chopper is described in this subclause.

The following data are necessary for the analysis:

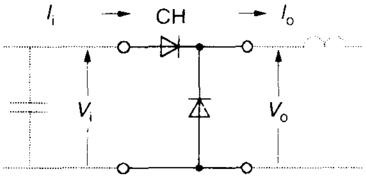
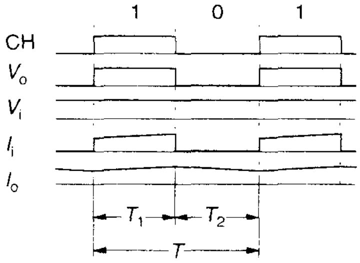
- average input voltage;
- average output current;
- chopping frequency;
- inductances of the output side;
- frequency characteristics of the input filter;
- conduction ratio $\alpha$.

The following information is obtained:

- output voltage;
- frequency spectrum of the output voltage;
- frequency spectrum of the output current;
- average input current;
- frequency spectrum of the input current;
- source-side current;
- critical operation of a continuous output-current mode.

The operation of a step-down chopper is shown in table 9.

**Table 9 – Operation of step-down chopper**

| Chopper | Chopper circuit | Waveforms |
|---|---|---|
| Step-down |  |  1<br>0<br>1<br>CH<br>$V_o$<br>$V_i$<br>$I_i$<br>$I_o$<br>$T_1$<br>$T_2$<br>$T$ |

### 3.3.6.1.1 Output voltage

For an explanation of output voltage, see 3.3.3.4 concerning basic characteristics of choppers.

### 3.3.6.1.2 Frequency spectrum of the output voltage

The output voltage consists of d.c. and harmonic waves whose fundamental frequency is the chopping frequency. The frequency spectrum of output voltage harmonics is calculated by the following formula:

$$V_o\,(n) = \frac{\sqrt{2}\,V_i}{\pi\,n}\,(1 - \cos 2\,n\,\pi\,\alpha)^{1/2} \tag{5}$$

where the input voltage $V_i$ is assumed completely constant.

### 3.3.6.1.3 Frequency spectrum of the output current

One can calculate the $n$th harmonic wave $I_o\,(n)$ by using $V_o\,(n)$, as defined in 3.3.6.1.2, in the following formula:

$$I_o\,(n) = \frac{V_o\,(n)}{Z_o\,(n)} \tag{6}$$

where $Z_o\,(n)$ is the total impedance on the output side for the frequency of the $n$th harmonic wave.

### 3.3.6.1.4 Average input current

The average input current $I_i$ is obtained by multiplying the conduction ratio $\alpha$ by the average output current $I_o$.

$$I_i = \alpha \times I_o \tag{7}$$

### 3.3.6.1.5 Frequency spectrum of the input current

The input current consists of d.c. and harmonic waves whose fundamental frequency is the chopping frequency. The frequency spectrum of input current harmonics is calculated by the following formula:

$$I_i\ (n) = \frac{\sqrt{2}\ I_o}{\pi n}\ (1 - \cos 2n\pi\alpha)^{1/2} \qquad (\mu = 0) \tag{8}$$

$$\begin{aligned} I_i\ (n) = \frac{I_o}{n\pi} \Big\{ 2\,(1 + \mu^2) + \frac{2\,\mu^2}{n^2\pi^2\alpha^2} - \frac{4\,\mu^2}{n\pi\alpha} \sin 2n\pi - \\ 2\,(1 - \mu^2 + \frac{\mu^2}{n^2\pi^2\alpha^2}) \cos 2n\pi\alpha \Big\}^{1/2} \qquad (\mu \neq 0) \end{aligned} \tag{9}$$

The accuracy of $I_i$ $(n)$ is only appropriate when ripples of the output current are large. The inaccuracy of formula (8), due to the ripples of the output current, is shown in the curves plotted in figure 30.

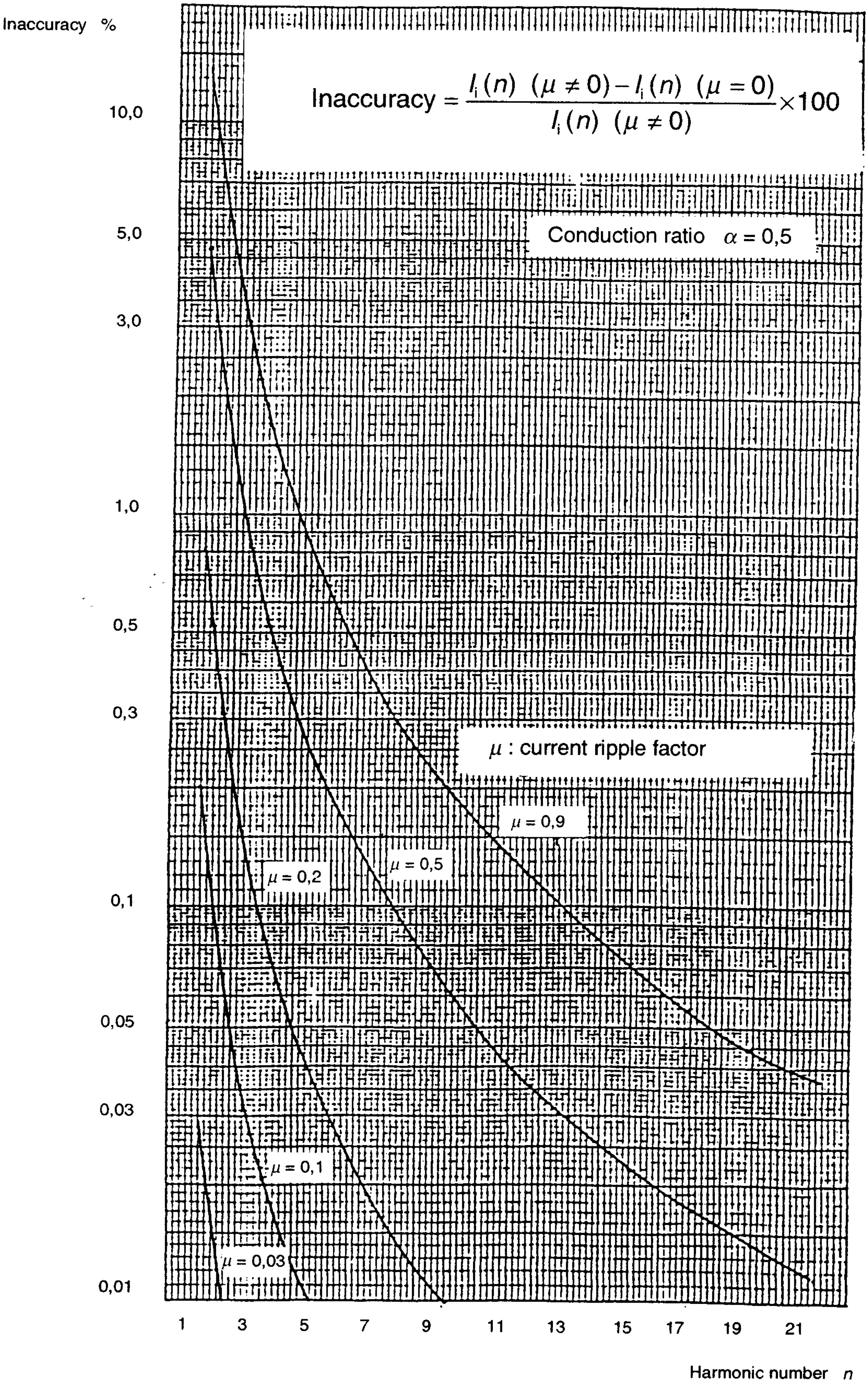
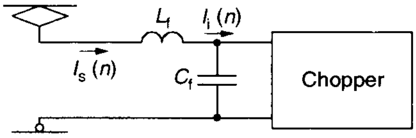


**Figure 30 – Inaccuracy due to the ripple of an output current**

#### 3.3.6.1.6 Source side current

##### 3.3.6.1.6.1 Circuit on the input side of a chopper

The filter illustrated in figure 31 is connected to the input circuit of a chopper. The current ripples produced by the chopper flow into the power source after they have been reduced in the filter.



$I_i(n)$: $n$th harmonic of chopper input current
$I_S(n)$: $n$th harmonic of line current
$L_f$: total inductance of the filter reactor, power line and substations

**Figure 31 – Circuit on the input side of a chopper**

##### 3.3.6.1.6.2 Calculation of the ripple currents into the power source

The current into the power source is calculated by multiplying the input harmonic currents of the chopper by the current reduction factor $\zeta_n$ as follows:

$$I_s(n) = \zeta_n I_i(n) \tag{10}$$

##### 3.3.6.1.6.3 Frequency characteristics of the input

The input-current reduction factor $\zeta_n$ is obtained from a chart, such as that shown in figure 32, or approximately from the following formula:

$$\zeta_n \approx \frac{1}{\left|1 - 4\pi^2 n^2 f_c{}^2 L_f C_f\right|} \tag{11}$$

where

$f_c$ is the frequency of the chopper;

$n$ is the harmonic number of the chopper frequency;

$L_f$ is the summation of the inductances of the filter reactor, power line and substations;

$C_f$ is the capacitance of the filter capacitor.

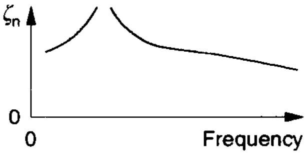


**Figure 32 – Frequency characteristics of the input**

### 3.3.6.1.7 Critical operation of a continuous output current mode

### 3.3.6.1.7.1 Continuous/intermittent output current modes

Three modes of output current exist:

a) continuous output: the instantaneous value of the output current is always positive;

b) critical operation: boundary between continuous and intermittent output current modes;

c) intermittent output: the instantaneous value of the output current is zero during a certain time.

### 3.3.6.1.7.2 Critical operation (see figures 33 and 34)

The current ripple $\Delta I_0$ in the continuous output current mode is described in the following formula and is identical to formula (3):

$$\Delta I_0 = \frac{V_i \, T \alpha (1-\alpha)}{L_0} \qquad (12)$$

where $\Delta I_0$ is a function of the conduction ratio $\alpha$, where $\Delta I_{0\,max}$ at $\alpha = 0{,}5$.

The average current $I_0$ at the critical operation is also a function of $\alpha$, since $I_0$ at the critical point is equal to ½ $\Delta I_0$.

$$I_{0B} = \frac{V_i \, T \alpha (1-\alpha)}{2 \, L_0} = K \alpha (1-\alpha) \qquad (13)$$

$$K = \frac{V_i \, T}{2 \, L_0} \qquad (14)$$

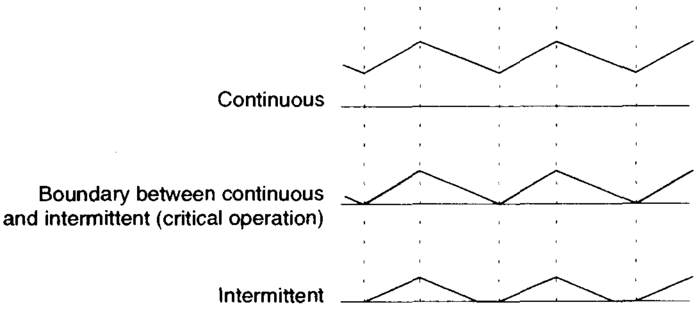

Continuous
Boundary between continuous and intermittent (critical operation)
Intermittent

Figure 33 – Waveforms of output currents of a chopper

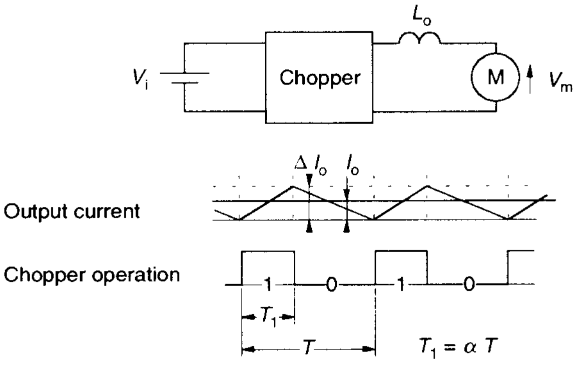


Figure 34 – Operation of boundary between continuous and intermittent

The output current is continuous when the average output current $I_o$ is larger than $I_{oB}$ and vice versa. The relation between the output current and the conduction ratio is illustrated in figure 35.

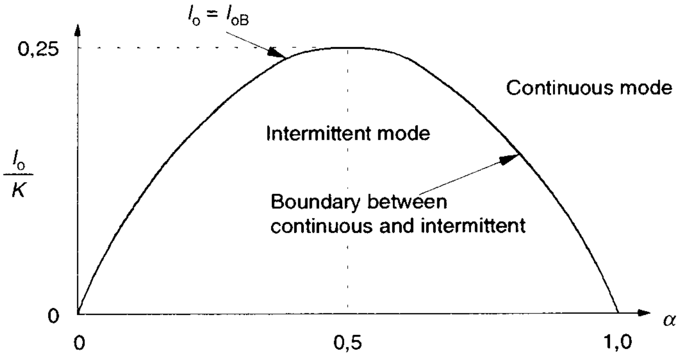


Figure 35 – Relation between the conduction ratio and continuous/intermittent output current modes

### 3.3.6.2 Step-up chopper

Only a single-phase chopper is described in this subclause. The following data are necessary for the analysis:

- average input voltage;
- average output current;
- chopping frequency;
- inductances on the input side;
- frequency characteristics of the output filter;
- conduction ratio $\alpha$.

The following information is obtained:

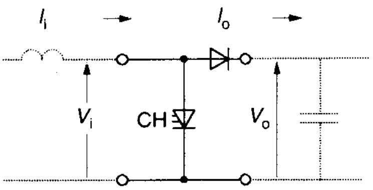
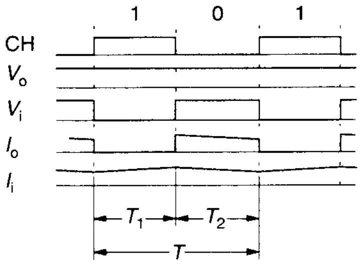
- input voltage;
- frequency spectrum of the input voltage;
- frequency spectrum of the input current;
- average input current;
- frequency spectrum of the output current;
- load-side current.

Operation of a step-up chopper is shown in table 10.

### 3.3.6.2.1 Input voltage

For an explanation of input voltage, see 3.3.3 concerning basic characteristics of choppers.

**Table 10 – Operation of step-up chopper**

| Chopper | Chopper circuit | Waveforms |
|---|---|---|
| Step-up |  |  1<br>0<br>1<br>CH<br>$V_o$<br>$V_i$<br>$I_o$<br>$I_i$<br>$T_1$<br>$T_2$<br>$T$ |

### 3.3.6.2.2 Frequency spectrum of the input voltage

The input voltage consists of d.c. and harmonic waves whose fundamental frequency is the chopping frequency. The frequency spectrum of the input voltage is calculated by the following formula:

$$V_i\,(n) = \frac{\sqrt{2}\,V_o}{\pi n}\,(1 - \cos 2n\pi\alpha)^{1/2} \qquad (15)$$

where the output voltage $V_0$ is assumed completely constant.

### 3.3.6.2.3 Frequency spectrum of the input current

The *n*th harmonic wave $I_i\,(n)$ can be calculated by using $V_i\,(n)$ as defined in 3.3.6.2.2 in the following formula:

$$I_i\,(n) = \frac{V_i\,(n)}{Z_i\,(n)} \qquad (16)$$

where $Z_i\,(n)$ is the total impedance on the input side for the frequency of the *n*th harmonic wave.

### 3.3.6.2.4 Average output current

The average output current $I_o$ is obtained by multiplying the conduction ratio of the diode arm $(1 - \alpha)$ by the average input current $I_i$.

$$I_o = (1 - \alpha)\ I_i \qquad (17)$$

### 3.3.6.2.5 Frequency spectrum of the output current

The output current consists of d.c. and harmonic waves whose fundamental frequency is the chopping frequency. The frequency spectrum of output current harmonics is calculated by the following formula:

$$I_o\ (n) = \frac{\sqrt{2}\ I_i}{\pi n}\ (1 - \cos 2n\pi\alpha)^{1/2} \qquad (\mu = 0) \qquad (18)$$

$$I_o\ (n) = \frac{I_i}{n\pi} \left\{ 2(1+\mu^2) + \frac{2\mu^2}{n^2\pi^2\alpha^2} - \frac{4\mu^2}{n\pi\alpha} \sin 2n\pi - \right.$$
$$\left. 2(1-\mu^2 + \frac{\mu^2}{n^2\pi^2\alpha^2}) \cos\ 2n\pi\alpha \right\}^{1/2} \qquad (\mu \neq 0) \qquad (19)$$

The accuracy of $I_o$ $(n)$ is only approximate when ripples of the input current are large. The inaccuracy of formula (18), due to the ripples of the input current, is shown in figure 36.

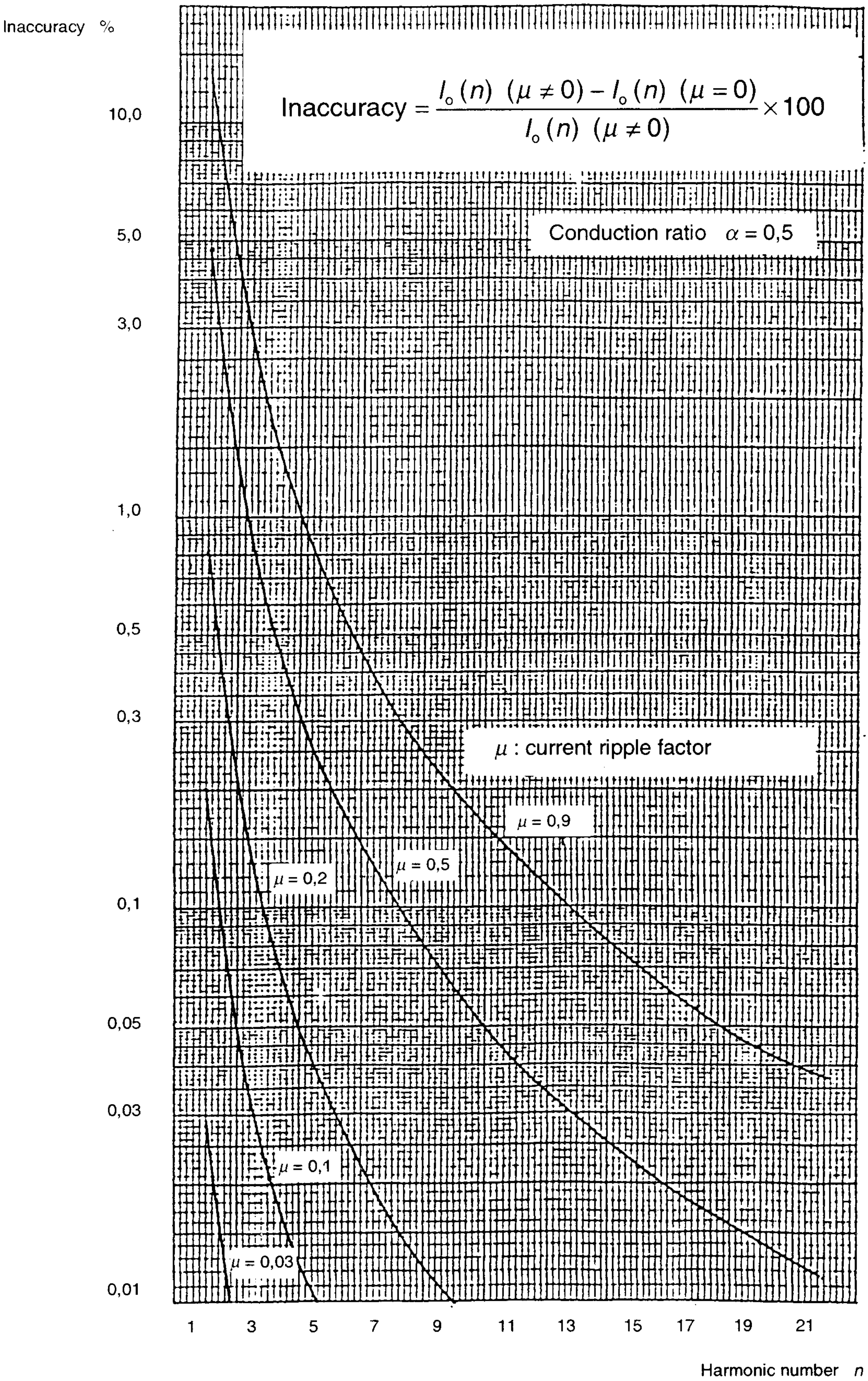
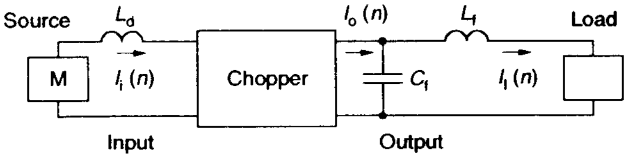


**Figure 36 – Inaccuracy due to the ripple of an input current**

### 3.3.6.2.6 Load-side current

#### 3.3.6.2.6.1 Circuit on the output side of a chopper

The filter illustrated in figure 37 is connected to the output circuit of a chopper. The current ripples produced in the chopper flow into the load after they have been reduced in the filter.



$I_i (n)$: input current
$I_l (n)$: load current
$L_f$: total inductance of filter reactor and load
$C_f$: capacitance of filter capacitor

**Figure 37 – Circuit in the output side of a chopper**

#### 3.3.6.2.6.2 Calculation of the ripple currents into the load

The current into the load is calculated by multiplying the output harmonic currents of the chopper by the current reduction factor $\zeta_n$ as follows:

$$I_i (n) = \zeta_n I_o (n) \tag{20}$$

#### 3.3.6.2.6.3 Frequency characteristics of the output

The output current reduction factor $\zeta_n$ is obtained from a chart, such as that shown in figure 38, or approximately from the following formula:

$$\zeta_n \approx \frac{1}{\left|1 - 4\pi^2 n^2 f_c^{\,2} L_f C_f\right|} \tag{21}$$

where

$f_c$ is the frequency of the chopper, in hertz;
$n$ is the harmonic number of the chopper frequency;
$L_f$ is the summation of the inductances of the filter reactor and load;
$C_f$ is the capacitance of the filter capacitor.

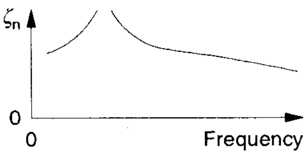


**Figure 38 – Frequency characteristics of the output**

### 3.3.6.2.7 Critical operation of a continuous input current mode

#### 3.3.6.2.7.1 Continuous/intermittent input current modes

Three modes of input current exist:

a) continuous input-current operation: the instantaneous value of the input current is always positive;

b) critical operation: boundary between continuous and intermittent input current modes;

c) intermittent input current: the instantaneous value of the input current is zero during a certain time.

#### 3.3.6.2.7.2 Critical operation (see figures 39 to 41)

The current ripple $\Delta I_\mathrm{i}$, in the continuous input current mode, is described in the following formula and is identical to formula (3):

$$\Delta I_\mathrm{i} = \frac{V_\mathrm{o}\, T \alpha (1-\alpha)}{L_\mathrm{i}} \qquad (22)$$

where $\Delta I_\mathrm{i}$ is a function of the conduction ratio $\alpha$ which is maximum $\Delta I_{\mathrm{i}\ \mathrm{max}}$ at $\alpha = 0{,}5$.

The average current $I_\mathrm{i}$ at the critical operation is also a function of $\alpha$, since $I_\mathrm{i}$ at the critical point is equal to $\frac{1}{2}\,\Delta I_\mathrm{i}$.

$$I_\mathrm{iB} = \frac{V_\mathrm{o}\, T \alpha (1-\alpha)}{2\, L_\mathrm{i}} = K\, \alpha (1-\alpha) \qquad (23)$$

$$K = \frac{V_\mathrm{o}\, T}{2\, L_\mathrm{i}} \qquad (24)$$

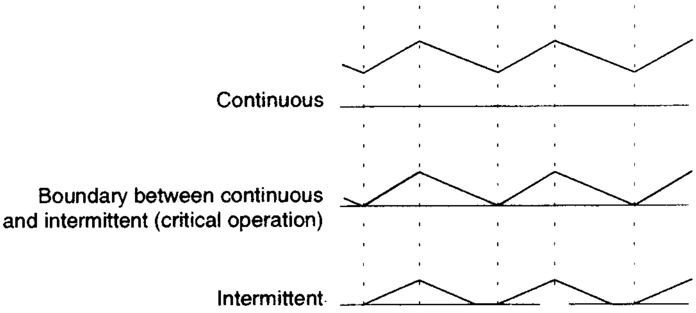

Continuous
Boundary between continuous and intermittent (critical operation)
Intermittent

**Figure 39 – Waveforms of the input current of a chopper**

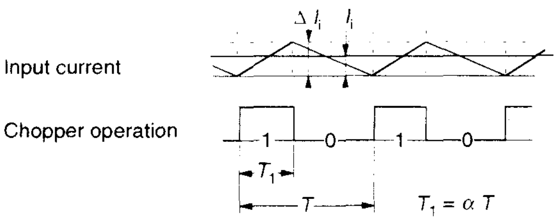


**Figure 40 – Relation between the conduction ratio and continuous/intermittent input current modes**

The input current is continuous when the average input current $I_i$ is larger than $I_{iB}$ and vice versa. The relation between the input current and the conduction ratio is illustrated in figure 41.

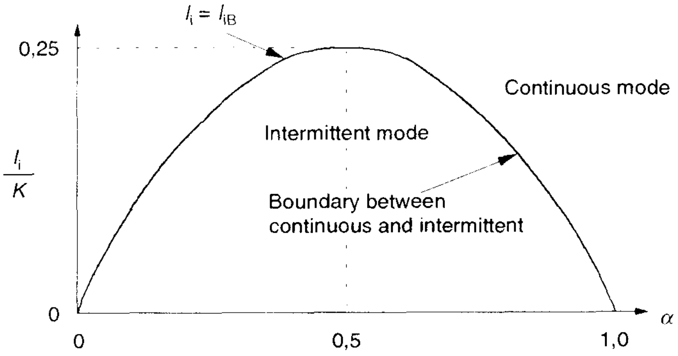
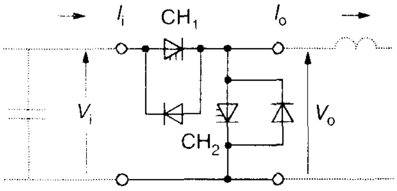


**Figure 41 – Relation between the conduction ratio and continuous/intermittent input current modes**

### 3.3.6.3 Current-stiff, two-quadrant chopper

The operation is either step-up or step-down since the chopper consists of two chopping units as illustrated in table 11. The characteristics of each unit are, therefore, identical to those of the step-up and step-down choppers (see 3.3.6.1 and 3.3.6.2).

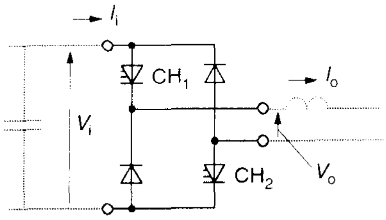
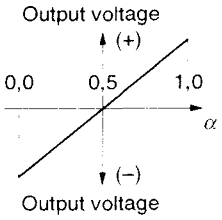
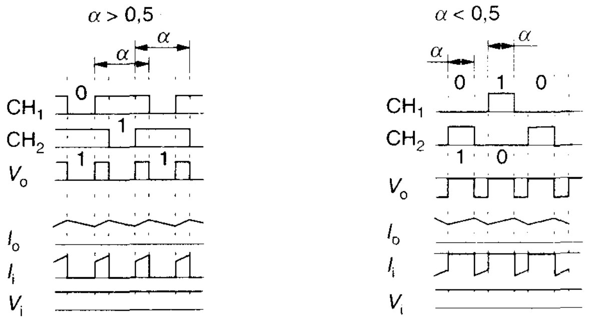
**Table 11 – Operation of a current-stiff, two-quadrant chopper**

| Circuit | Operation of chopping part | Characteristics |
|---|---|---|
|  | $CH_1$: Operational<br>$CH_2$: Off | Same as step-down chopper |
| | $CH_1$: Off<br>$CH_2$: Operational | Same as step-up chopper but output of step-up chopper changes to input and current polarity of step-up chopper reverses |

### 3.3.6.4 Voltage-stiff, two-quadrant chopper

The operation is either step-up or step-down since the chopper consists of two chopping units as illustrated in table 12. The characteristics of each unit are, therefore, identical to those of the step-up and step-down choppers (see 3.3.6.1 and 3.3.6.2).

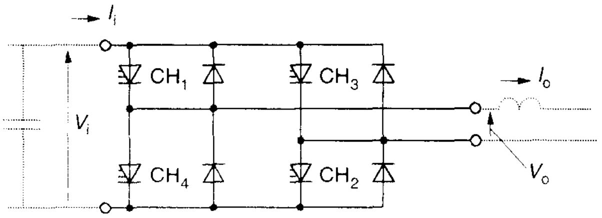
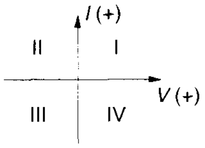
**Table 12 – Operation of a voltage-stiff two-quadrant chopper**

| | |
|---|---|
| **Circuit** |  |
| **Operation of chopper (CH)** | 1) The difference between phase of CH$_1$ and CH$_2$ is 180°<br>2) The conduction intervals of CH$_1$ and CH$_2$ are the same<br>3) Characteristics (figure on the right)<br>(1) $\alpha > 0,5$ — Output voltage >0<br>(2) $\alpha < 0,5$ — Output voltage <0<br>(3) $\alpha = 0,5$ — Output voltage =0<br> <br> |
| **Characteristics** | Characteristics are those of step-down and step-up choppers where $\alpha$ and $f$ of the voltage-stiff two-quadrant chopper changes to $\alpha'$ and $f'$ as follows:<br>$f' = 2f$ $f'$, $\alpha'$: Frequency, conduction ratio of step-down or step-up chopper<br>$\alpha' = \lvert 2\alpha - 1 \rvert$<br>1) $\alpha > 0,5$ — Same as characteristics of step-down chopper<br>2) $\alpha < 0,5$ — Same as characteristics of step-up chopper |

### 3.3.6.5 Four-quadrant chopper

The operation is that of a voltage-stiff, two-quadrant chopper, whose output current direction is reversible, since the chopper consists of four chopping units as illustrated in table 13. The characteristics of each unit are, therefore, identical to those of the step-up and step-down choppers (see 3.3.6.1 and 3.3.6.2).

**Table 13 – Operation of a four-quadrant chopper**

| | |
|---|---|
| **Circuit** |  $I_i$<br>$V_i$<br>$CH_1$<br>$CH_3$<br>$CH_4$<br>$CH_2$<br>$I_o$<br>$V_o$ |
| **Operation of chopper (CH)** | 1) Quadrant<br>Quadrants number (I, II, III and IV) are shown in the figure on the right  <br>2) Operation in quadrants I and II<br>$CH_1$, $CH_2$: chopping operation<br>$CH_3$, $CH_4$: off<br>Operation is the same as voltage-stiff, two-quadrant chopper<br>3) Operation in quadrants III and IV<br>$CH_3$, $CH_4$: chopping operation<br>$CH_1$, $CH_2$: off<br>Operation is the same as the operation of a chopper whose chopper number in voltage-stiff, two-quadrant chopper changes as follows:<br>$CH_1 \Rightarrow CH_3$, $CH_2 \Rightarrow CH_4$, and output current polarity reverses |
| **Characteristics** | 1) Operation in quadrants I and II<br>Characteristics are the same as characteristics of voltage-stiff, two-quadrant chopper<br>$\alpha > 0,5$ – Same as characteristics of quadrant I<br>$\alpha < 0,5$ – Same as characteristics of quadrant II<br>2) Operation in quadrants III et IV<br>Characteristics are the same as characteristics of voltage-stiff, two-quadrant chopper whose current polarity reverses<br>$\alpha > 0,5$ – Same as characteristics of quadrant III<br>$\alpha < 0,5$ – Same as characteristics of quadrant IV |

## 3.4 Inverters

### 3.4.1 Classification of inverters

Inverters are classified according to the following criteria:

a) commutation – external/self-commutated;
b) phase number – single-phase/multi-phase;
c) power source – voltage-stiff/current-stiff;
d) configuration – full-bridge/half-bridge;
e) control scheme – PWM controlled/rectangular wave-controlled;
f) output level – two-level/multilevel.

The classification is summarized in table 14.

Table 14 – Inverter classification

| Classification | Name | Definition |
|---|---|---|
| Commutation | External commutation | Commutation by power source or load |
| | Self-commutated | Commutating function inside of the inverter itself |
| Phase number | Single-phase | Single-phase output |
| | Three-phase | Three-phase output |
| | Multiphase | Multiphase output |
| Power source | Voltage-stiff | The inverter has a capacitor on the input side and works as a voltage source |
| | Current-stiff | The inverter has a reactor on the input side and works as a current source |
| Configuration | Full-bridge | Every terminal of the load is connected with a switching arm |
| | Half-bridge | One side of the output is taken from an inverter arm, and the other side from the middle point of the power source |
| Control scheme | PWM controlled | The magnitude of the output current/voltage is controlled with a PWM scheme |
| | Rectangular wave controlled | The output current/voltage is a rectangular waveform |
| Output voltage levels | Two-levels | The output voltage has two-level values: 0 and 1 time the input voltage level |
| | Multilevel (*n*-level) | The output voltage has multilevel values: 0,1/(*n* – 1)...<br>One time the input voltage level |

### 3.4.2 Circuits

### 3.4.2.1 Voltage-stiff inverters

The input d.c. voltage is converted to the output a.c. voltages by on/off switching in a voltage-stiff inverter. Typical switching behaviours are illustrated in figures 42 and 43 for single-phase and three-phase commutations, respectively. The basic circuit configuration of a voltage-stiff inverter is given in figure 44.

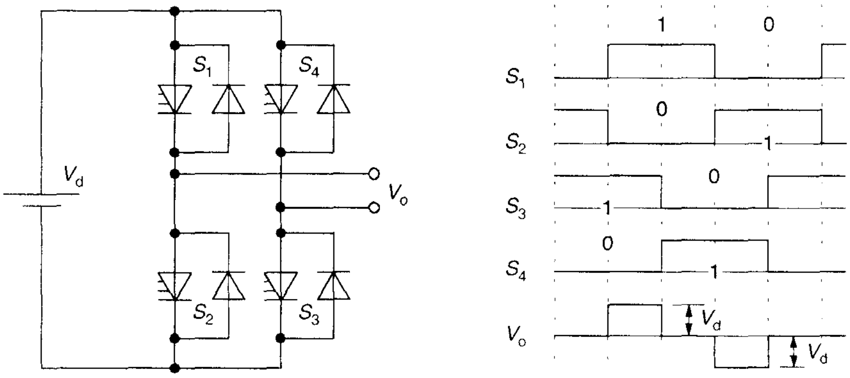


Figure 42 – Full bridge, single-phase, voltage-stiff inverter

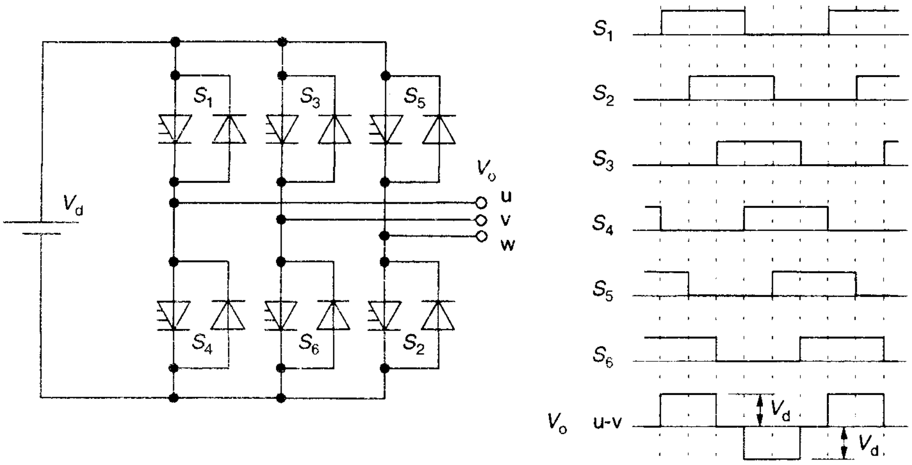


Figure 43 – Full bridge, three-phase, voltage-stiff inverter

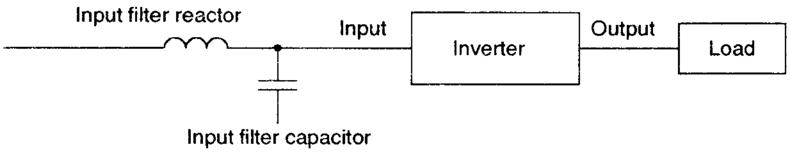


Figure 44 – Basic circuit configuration of a voltage-stiff inverter

### 3.4.2.2 Current-stiff inverters

The input direct current is converted to the output alternating currents by on/off-switching in a current-stiff inverter. Typical switching behaviours are illustrated in figure 45 and figure 46 for single-phase and three-phase commutations, respectively. The basic circuit configuration of current-stiff inverter is given in figure 47.

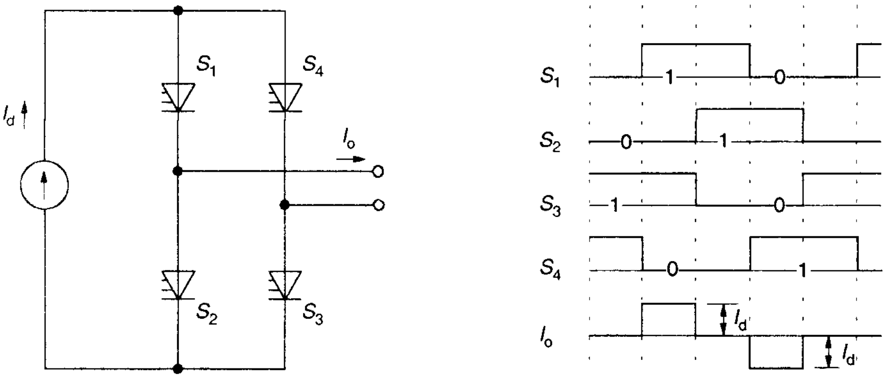


Figure 45 – Full-bridge, single-phase inverter

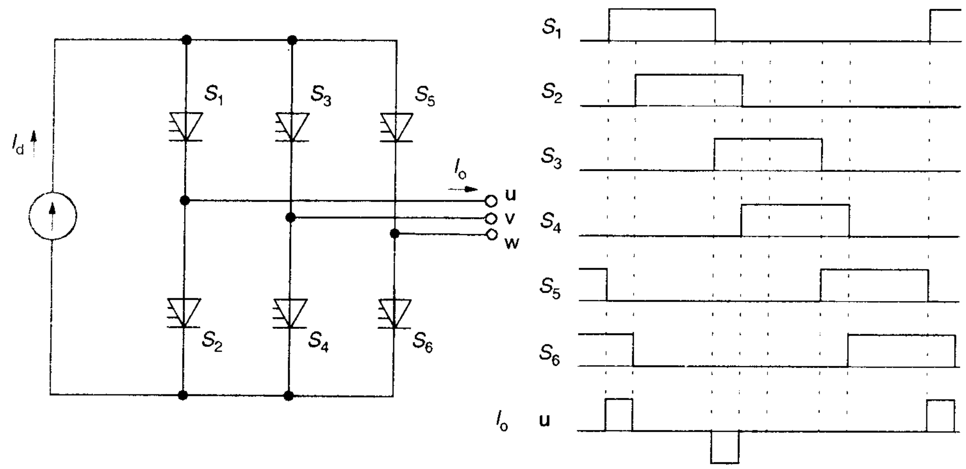


Figure 46 – Full-bridge, three-phase inverter

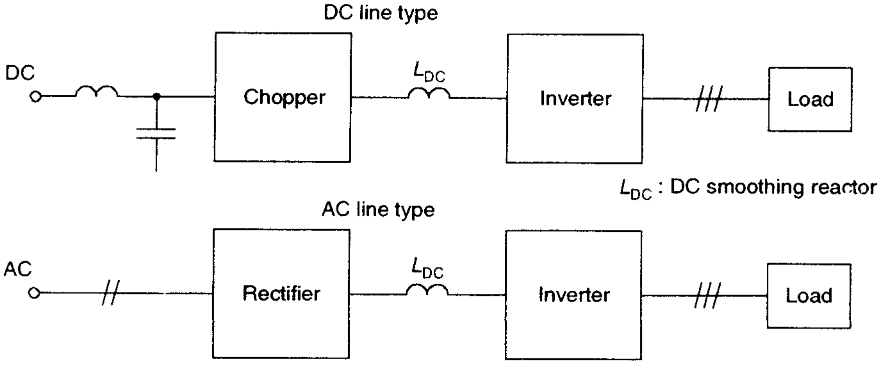


Figure 47 – Basic circuit configuration of a current-stiff inverter

### 3.4.3 Basic characteristics

Basic characteristics of three-phase inverters are described in the following subclauses.

#### 3.4.3.1 Voltage-stiff inverters

#### 3.4.3.1.1 Basic waveform

Typical input/output wave-forms of a three-phase, voltage-stiff inverter are illustrated in figure 48.

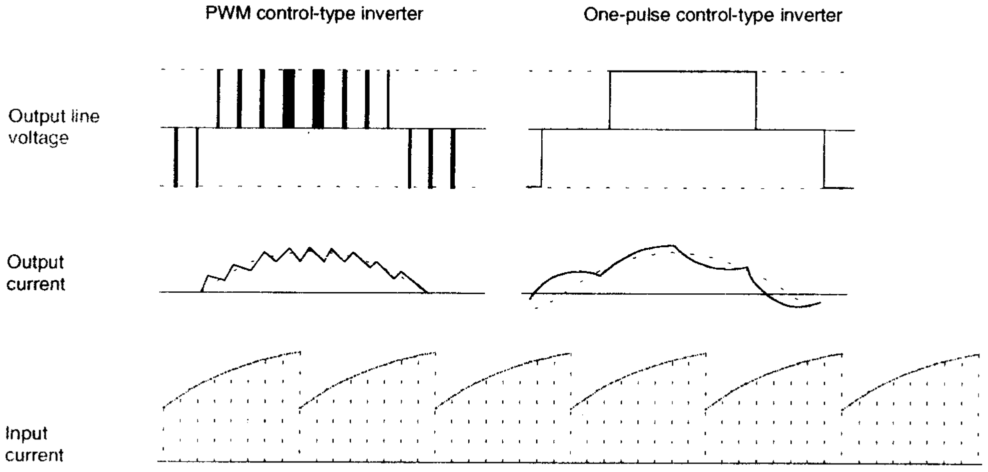


Figure 48 – Typical input/output waveforms of a three-phase, voltage-stiff inverter

#### 3.4.3.1.2 Basic behaviour

a) Input side of the inverter

- In PWM control-type converters, the current waveform consists of pulses whose trace line is the rectified waveform of the a.c. output load currents, and it contains harmonics whose fundamental frequency is six times that of the fundamental frequency of the inverter besides the d.c. component.
- In one-pulse control-type converters, the current waveform is the rectified waveform of the a.c. output load currents, and it contains harmonics whose fundamental frequency is six times that of the fundamental frequency of the inverter besides the d.c. component.
- The a.c. components of the current in the d.c. input side are reduced to the value determined by frequency characteristics of the input filter.
- The voltage ripple on the input side is determined by the a.c. components in the input current and the capacity of the filter capacitor.

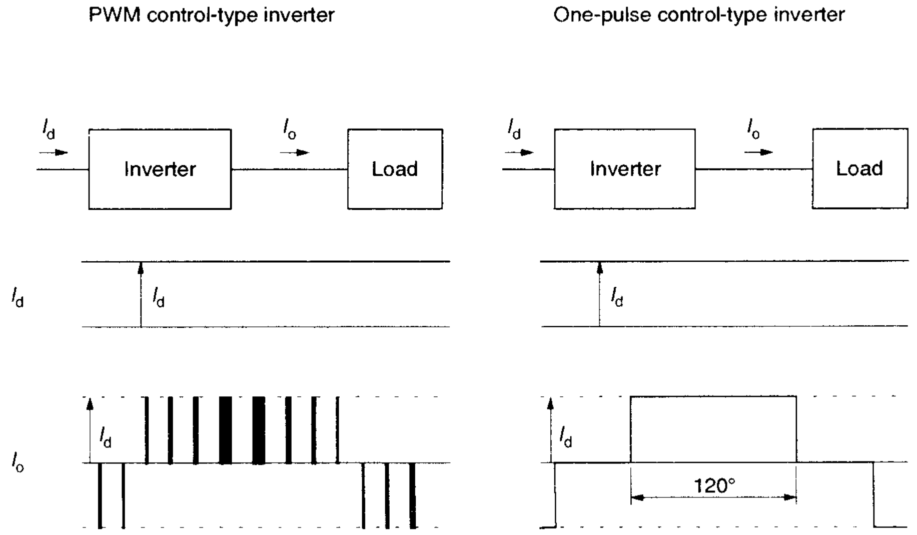
b) Output side of the inverter

- The voltage waveform consists of pulses whose instantaneous value is equal to ± the d.c. input voltage and contains harmonics whose fundamental frequency is the same as that of the inverter.
- The current harmonics which flow into the load are determined by the voltage harmonics and the impedance in the a.c. load side.

### 3.4.3.2 Current-stiff inverters

#### 3.4.3.2.1 Basic waveform

Typical input/output waveforms of a three-phase current-stiff inverter are illustrated in figure 49.


PWM control-type inverter

One-pulse control-type inverter

**Figure 49 – Typical input/output waveform of a three-phase, current-stiff inverter**

#### 3.4.3.2.2 Basic behaviour

a) Output side of the inverter

- The waveform of the inverter output current $I_0$ consists of pulses whose instantaneous values are equal to ± the input current.
- The current contains the harmonics whose fundamental frequency is identical to the inverter frequency.
- The output voltage is determined by the output current and the impedance of the loads.
- If the load is a motor, the output voltage waveform is the summation of the induced voltage of the motor and the voltages across motor windings due to the leakage impedance.

b) Input side of the inverter

- The voltage waveform is identical to the rectified load voltage.

### 3.4.4 Basic control scheme of inverters

Synchronous/asynchronous modulation methods exist with various carrier waveforms for the PWM controls.

#### 3.4.4.1 Synchronous/asynchronous PWM

The two methods are outlined in figure 50.

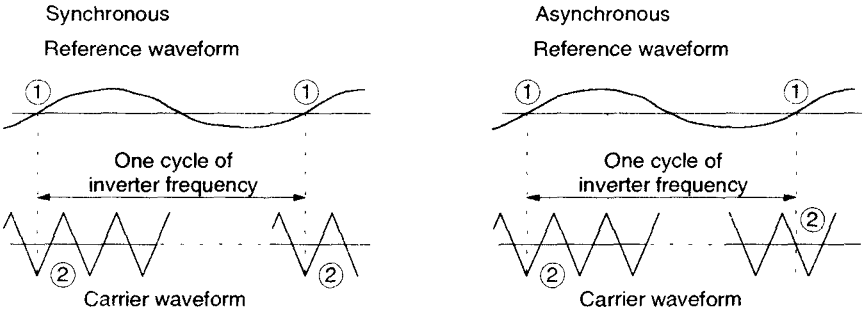


Figure 50 – Synchronous/asynchronous PWM

#### 3.4.4.2 Carrier waveforms

Typical PWM schemes are summarized in table 15. The behaviour of the two typical PWM schemes is illustrated in figure 51.

Other methods which exist to generate PWM control can also be used.

**Table 15 – Typical modulation schemes**

| Carrier waveform | Reference waveform | Modulation scheme |
|---|---|---|
| Triangular wave | Sinusoidal wave | Sinusoidal-triangular wave modulation |
| Triangular wave | Rectangular wave | Rectangular-triangular wave modulation |

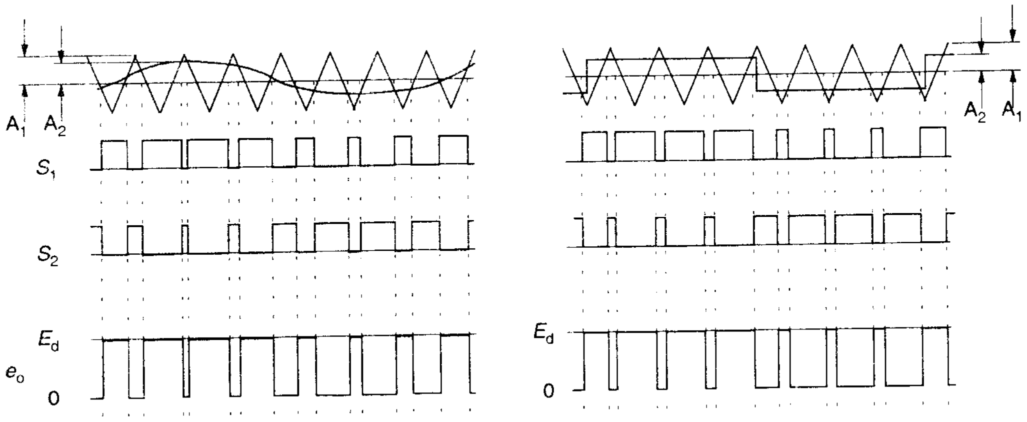
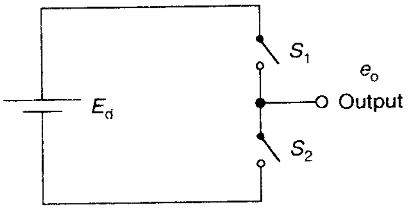


**Figure 51a – Sinusoidal-triangular wave modulation**

**Figure 51b – Rectangular-triangular wave modulation**



Modulation ratio $\gamma = \frac{A_2}{A_1}$

$A_1$: amplitude of carrier wave

$A_2$: amplitude of reference wave

**Figure 51 – Typical PWM schemes**

### 3.4.5 Combination of inverters

It is possible to have two or more inverters connected in parallel or in series with or without shifting phase angle among carrier waves.

Typical combinations are given in figure 52.

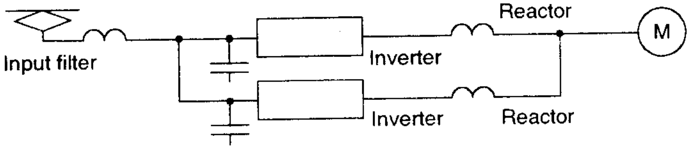
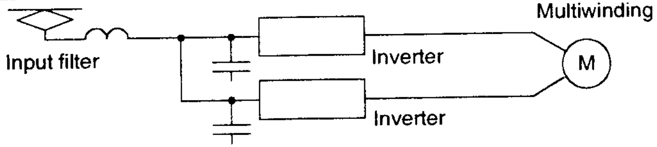
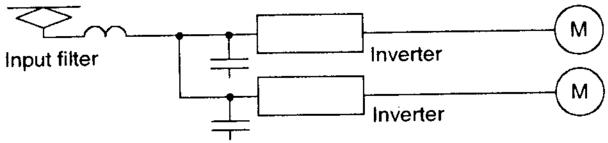
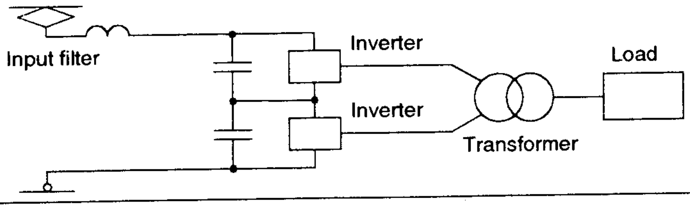
| Method | Typical configurations of multiple system |
|---|---|
| Parallel output |  Reactor<br>Input filter<br>Inverter<br>M<br>Inverter<br>Reactor |
| Multiwinding load |  |
| Parallel inverter |  |
| Series output |  |

**Figure 52 – Typical combinations of inverters**

### 3.4.6 Electric characteristics

This subclause concerns only three-phase, synchronous, voltage-stiff inverters.

#### 3.4.6.1 Harmonic output voltage

Harmonic output voltage charts as shown in figure 54, are found in inverters with synchronous modulation (see figure 53).

Parameters for charts:

a) modulation scheme;
b) modulation ratio;
c) number of pulses.

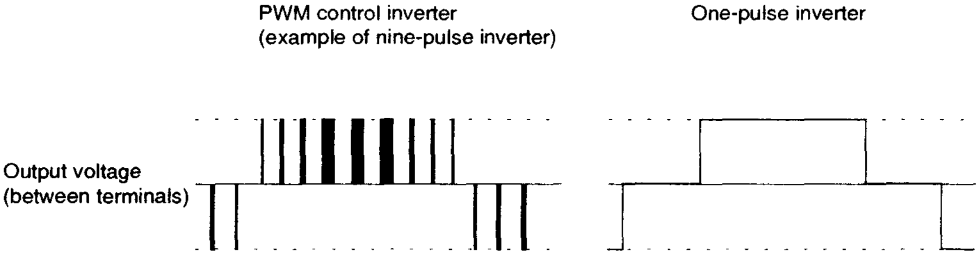


Figure 53 – Inverter output waveform

Parameter: modulation scheme number of pulses.

An example of sinusoidal-triangular modulation and nine pulses is given in figure 54.

*n*: harmonic number.

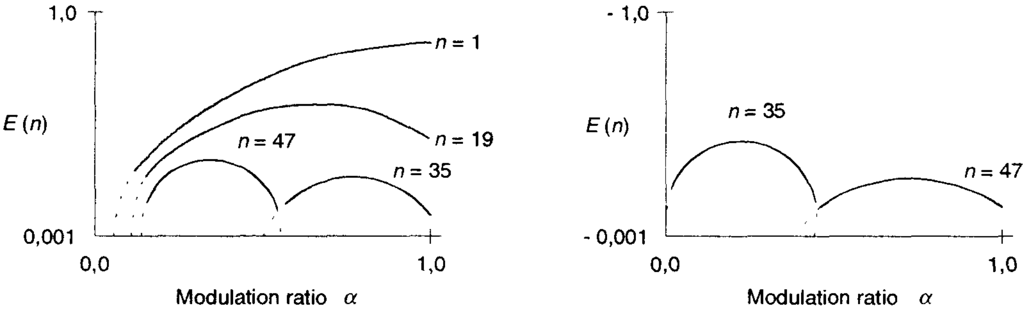


Figure 54 – Harmonic output voltage of an inverter

The input voltage is assumed completely constant in the charts, and $E(n)$ is defined as follows:

$$E(n) = \frac{\text{the } n\text{th harmonic output phase voltage}}{\text{input voltage}} \quad \text{(r.m.s.)} \qquad (25)$$

The parameters in the charts are summarized in table 16.

**Table 16 – Parameters for frequency spectrum of output voltage**

| Modulation type | Number of pulses | | Modulation ratio | |
|---|---|---|---|---|
| Sinusoidal-triangular | 27; 15; 9 | | 0,0 ~ 1,0 | |
| Rectangular-triangular | 3 | 1 | 0,6 ~ 1,0 | 1 |

The charts with values taken from table 16 are shown in figure A.12.

NOTE 1 In the charts, some of the harmonic phase voltages have negative values. The wave of the harmonic phase voltage with negative value shows negative-phase to the wave of the fundamental phase voltage. The wave of the harmonic phase voltage with positive value shows in-phase to the wave of the fundamental phase voltage.

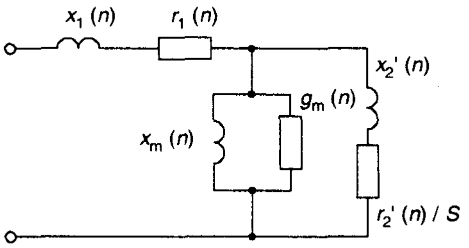
NOTE 2 The number of pulses is three times greater than the integral number.

### 3.4.6.2 Harmonic output current

Harmonic currents are derived from the harmonic voltages as described in 3.4.6.1 and from impedances in load circuits. Each harmonic current is calculated from the $n$th harmonic voltage, and the equivalent load circuit impedance for the $n$th harmonic wave. Skin effect and approximation effect should be considered when estimating the equivalent impedances. One method to simulate the load in steady-state condition is given in 3.4.6.2.1 to 3.4.6.2.3.

### 3.4.6.2.1 Asynchronous motor load

An equivalent circuit of an asynchronous motor for the $n$th harmonic voltage is given in figure 55.



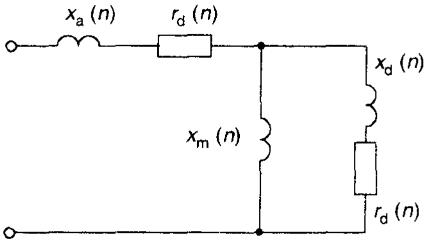
$x_1(n)$: primary $n$th harmonic reactance
$r_1(n)$: primary $n$th harmonic resistance
$x_2'(n)$: secondary $n$th harmonic reactance (converted to primary)
$r_2'(n)$: secondary $n$th harmonic resistance (converted to primary)
$x_m(n)$: $n$th magnetizing reactance
$g_m(n)$: $n$th magnetizing conductance
$n$: harmonic number
$S$: slip (in case of $n \geq 2$: $S = 1$)

NOTE Reactance and resistance at high frequency are considered of skin effect.

Figure 55 – Equivalent circuit of an asynchronous motor for the $n$th harmonic

#### 3.4.6.2.2 Synchronous motor load

The equivalent circuits for the *d*-axis and *q*-axis are symmetric, if the field circuit can be neglected. In this case, the synchronous machine is represented by the equivalent circuit shown in figure 56.



$x_a (n)$: *n*th harmonic leakage reactance of armature winding

$x_a (n)$: *n*th harmonic resistance of armature winding

$x_m (n)$: *n*th harmonic synchronizing reactance

$x_d (n)$: *n*th harmonic leakage reactance of damper winding

$r_d (n)$: *n*th harmonic resistance of damper winding

$n$: harmonic number

NOTE Reactance and resistance at high frequency are considered of skin effect.

**Figure 56 – Equivalent circuit of a synchronous motor for the *n*th harmonic ($n \geq 2$)**

#### 3.4.6.2.3 Calculation of harmonic output current

If resistance and magnetizing reactance in the load are disregarded, harmonic output current $I_0(n)$ can be calculated approximately from formula (26).

$$I_o (n) = \frac{E (n)}{X (n)} \tag{26}$$

where

$E (n)$ is the *n*th harmonic output phase voltage (r.m.s.), in volts;

$X (n)$ is the *n*th total reactance of the load.

NOTE $E (n)$ is shown in the charts given in annex A.

### 3.4.6.3 Harmonic input current

#### 3.4.6.3.1 Harmonic input current with output current, assumed to be a complete sinusoidal wave

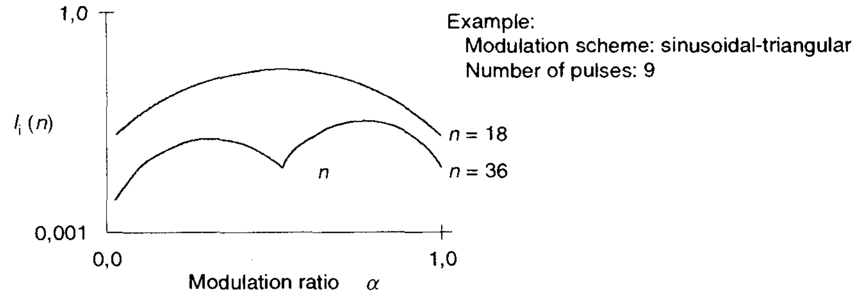
The harmonic input current is calculated from the output current, assumed to be a complete sinusoidal wave, and the charts such as the one in figure 57 are given in annex A.

List of parameters in the charts:

a) modulation scheme;
b) modulation ratio;
c) number of pulses;
d) displacement factor.

The output current is assumed completely sinusoidal and $I_i\ (n)$ in the charts is defined as follows:

$$I_i\ (n) = \frac{\text{the } n\text{th harmonic input current}}{\text{r.m.s. value of output current}} \tag{27}$$



Parameter: modulation scheme, number of pulses, displacement factor

Example:
Modulation scheme: sinusoidal-triangular
Number of pulses: 9

Figure 57 – Frequency spectrum of the input current of the inverter

The parameters in the charts are summarized in table 17.

**Table 17 – Parameters for frequency spectrum of input current**

| Modulation type | Displacement factor | Number of pulses | | Modulation ratio | |
|---|---|---|---|---|---|
| Sinusoidal<br>– triangular | 0,75; 0,8; 0,85; 0,9; 1,0 | 27; 15; 9 | | 0,0 ~ 1,0 | |
| Rectangular<br>– triangular | 0,75; 0,8; 0,85; 0,9; 1,0 | 3 | 1 | 0,6 ~ 1,0 | 1 |

The charts with values taken from table 17 are shown in figures A.13.

### 3.4.6.3.2 Harmonic input current with output current, not assumed to be a sinusoidal wave

Generally, the input current of the inverter, as shown in formula (28), is equal to harmonic current plus ripple current of the output current. In this case, the output current of the inverter is not assumed to be sinusoidal wave.

In the case of a non-sinusoidal wave, harmonic input current is different from that of a completely sinusoidal wave.

The $n$th harmonic input current is not more than $I'_i\ (n)$.

$$I'_i\ (n) = I_i\ (n) + |\Delta\ I_i\ (n)| \tag{28}$$

where

$I_i\ (n)$ is the harmonic input current, for a completely sinusoïdal wave of the output current, in amperes;

$|\Delta\ I_i\ (n)|$ is the harmonic input current by ripple current of the output current, in amperes.

$$|\Delta I_i (n)| \approx \sum_{m\,k}^{\infty} \left\{ \frac{E(k)\,E(m)}{\sqrt{2}\,m\,\%\,X} \right\} \tag{29}$$

$$n = |m \pm k| \qquad m = 2, 3, 4, \ldots\ldots \qquad k = 1, 2, 3, \ldots\ldots \tag{30}$$

$$\%\,X = \frac{I_{out}\,X\,(1)}{E_d} \tag{31}$$

where

$I_{out}$ is the output current of the inverter (r.m.s.), in amperes;

$X\,(1)$ is the total reactance of the load at fundamental frequency of the inverter;

$E\,(k)$ is the $k$th output phase voltage (r.m.s.), in volts;

$E\,(m)$ is the $m$th output phase voltage (r.m.s.), in volts.

NOTE Harmonic input current $I_i\,(n)$, $E\,(k)$ and $E\,(m)$ are given in annex A.

#### 3.4.6.3.3 Influence on harmonic input current by the harmonic output current

Harmonic input current is affected by the harmonic output current, as shown in formula (28).

Generally, the values of % $X$, $E\,(k)$ and $E\,(m)$ are given as follows:

$0{,}1 < \%\,X < 0{,}3$

$0{,}1 < E\,(k) < 0{,}3$

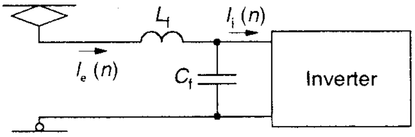
$0{,}1 < E\,(m) < 0{,}3$

If $n \geq 9$, $\Delta I_i\,(n)$ is less than a few per cent of the $I_i\,(n)$.

### 3.4.6.4 Calculation of harmonic currents in the power source

#### 3.4.6.4.1 Circuit on the input side of an inverter

The filter illustrated in figure 58 is connected to the input circuit of an inverter. The harmonic currents produced in the inverter flow into the power source after they have been reduced in the filter.



$I_i\,(n)$: $n$th harmonic of inverter input current

$I_e\,(n)$: $n$th harmonic of line current

$L_f$: inductance of the filter reactor

Figure 58 – Circuit on the input side of an inverter

#### 3.4.6.4.2 Calculation of the ripple currents in the power source

The current into the power source is calculated by multiplying the input harmonic currents of the inverter by the current reduction factor $\zeta_n$ as follows:

$$I_s(n) = \zeta_n I_i(n) \tag{32}$$

#### 3.4.6.4.3 Frequency characteristics of an input filter

The input current reduction factor $\zeta_n$ is obtained from a chart, such as that shown in figure 59, or approximately from the following formula:

$$\zeta_n \approx \frac{1}{\left|1-4\pi^2 n^2 f_i^2 L_f C_f\right|} \tag{33}$$

where

$f_i$ is the fundamental frequency of the inverter, in hertz;

$n$ is the harmonic number of the inverter frequency;

$L_f$ is the inductance of the filter reactor;

$C_f$ is the capacitance of the filter capacitor.

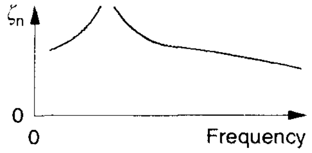


Figure 59 – Frequency characteristics of an input filter

## 4 Indirect convertors

### 4.1 Classification of indirect convertors

It is possible to use various types of convertors by combining unit convertors in the source and load sides. Typical configurations are shown in table 2.

### 4.2 Circuits and basic behaviour of indirect convertors

The circuit configurations and the basic behaviour of each convertor unit in the source and load sides are identical to those of the convertors described in 3.2 to 3.4.

### 4.3 Basic characteristics of the indirect convertors

The basic characteristics of each convertor unit in the source and load sides are identical to those of the convertors described in 3.2 to 3.4.

### 4.4 Control scheme of indirect convertors

The control scheme of each convertor unit in the source and load sides is identical to those of the convertors described in 3.2 to 3.4.

### 4.5 Multiple indirect convertors

The multiple configurations of each convertor unit in the source and load sides are identical to those of the convertors described in 3.2 to 3.4.

### 4.6 Analysis of indirect convertors

The calculated characteristics of each convertor unit in the source and load sides are identical to those of the convertors described in 3.2 to 3.4.

## 5 Convertors for multi-supply rolling stock

### 5.1 Classification of convertors

Various types of convertors are possible. The combination of unit convertors depends upon whether the power source and the load are a.c. or d.c. It is possible to have two or more configurations in one convertor to allow for different inputs.

Typical configurations are shown in table 3.

### 5.2 Circuits and basic behaviour of convertors

The circuit configurations and basic behaviour of each convertor unit in the source and load sides are identical to those of the convertors described in 3.2 to 3.4.

### 5.3 Basic characteristics of convertors

The basic characteristics of each convertor unit in the source and load sides are identical to those of the convertors described in 3.2 to 3.4.

### 5.4 Control scheme of convertors

The control scheme of each convertor unit in the source and load sides is identical to those of the convertors described in 3.2 to 3.4.

### 5.5 Multiple convertors

The multiple configurations of each convertor unit in the source and load sides are identical to those of the convertors described in 3.2 to 3.4.

### 5.6 Analysis of convertors

The calculated characteristics of each convertor unit in the source and load sides are identical to those of the convertors described in 3.2 to 3.4.

# Annex A
(normative)

## Graphic representations

Uniform convertor

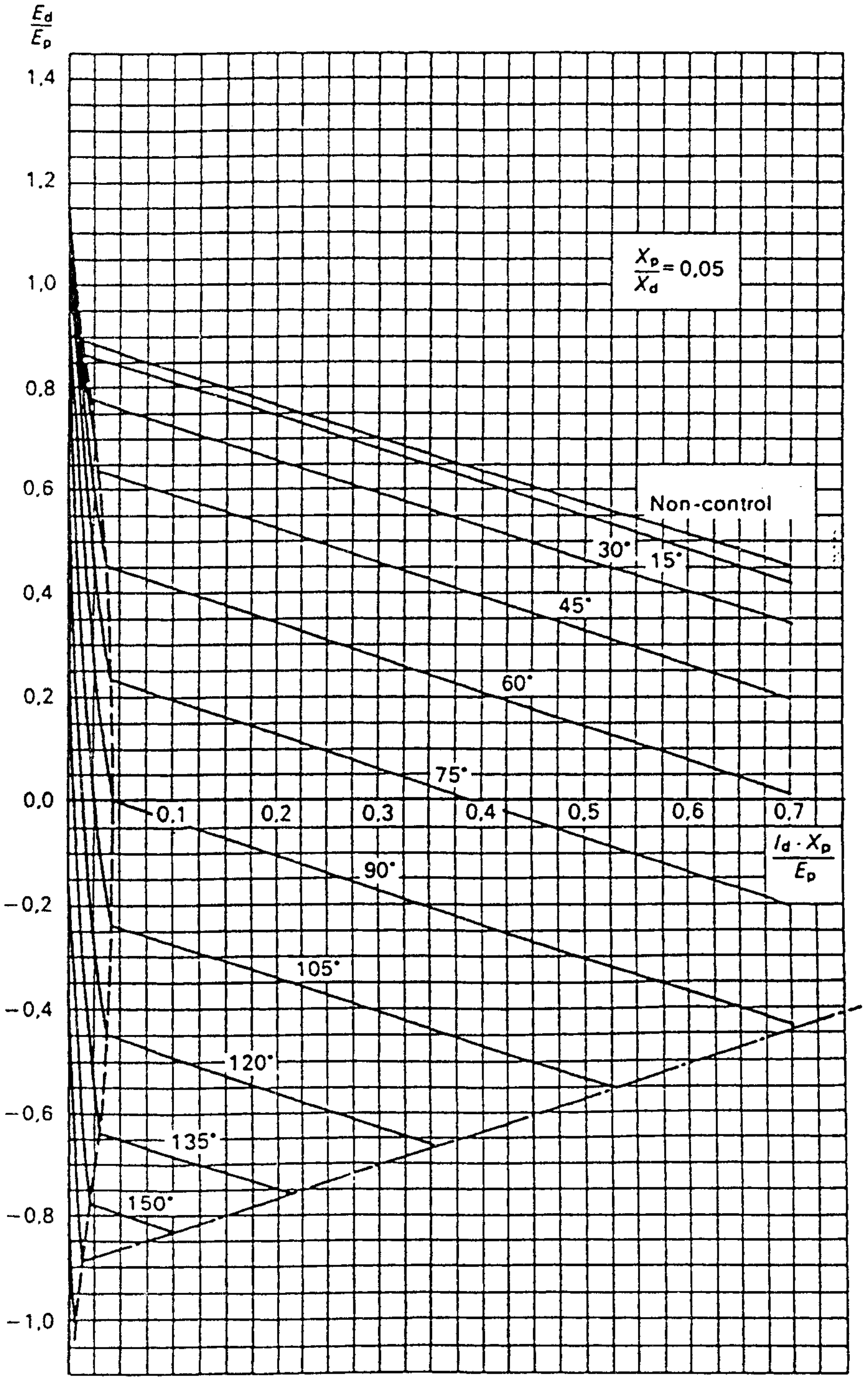


Figure A.1a

Figure A.1 – DC voltage regulation

Uniform convertor

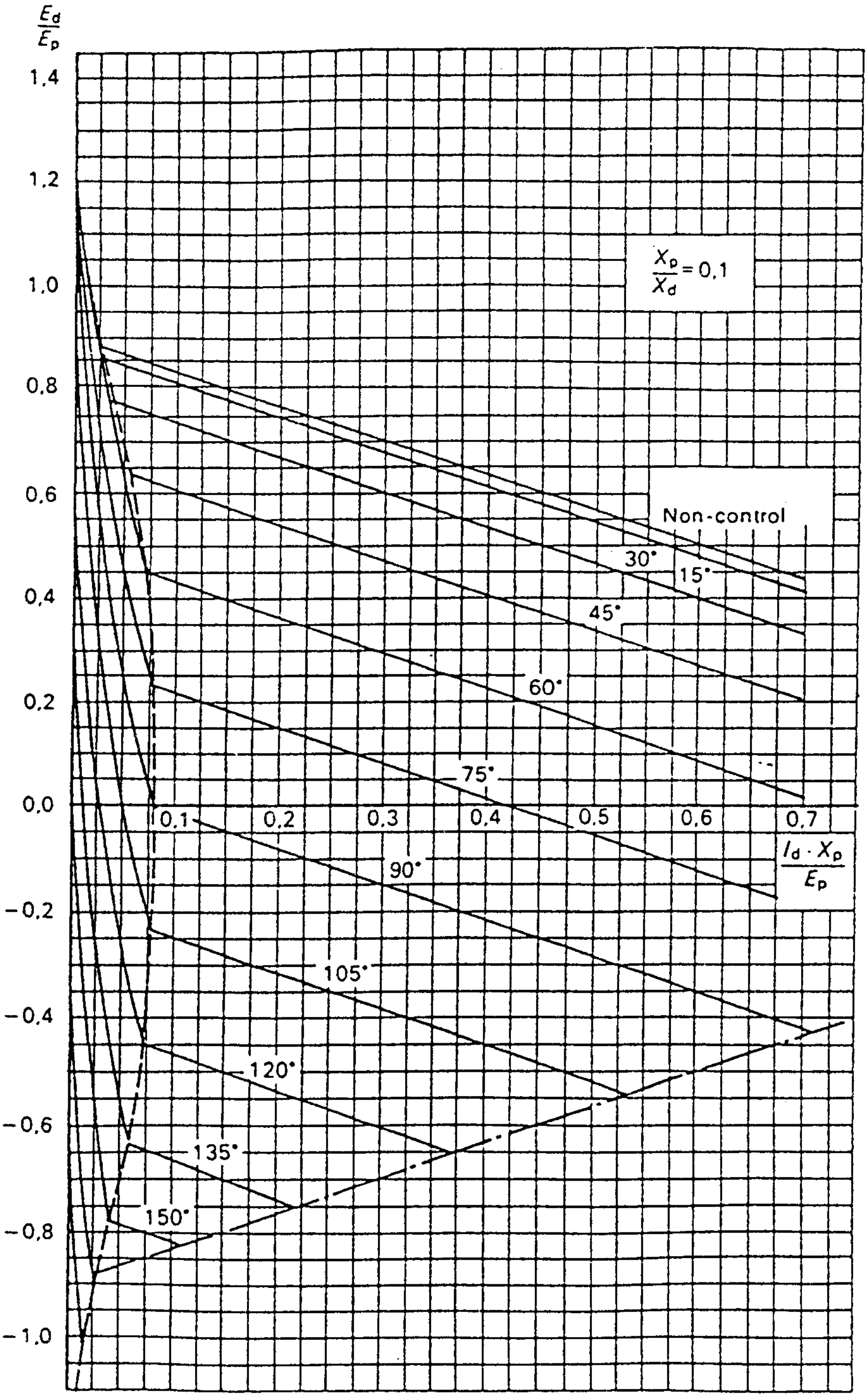


**Figure A.1b**

**Figure A.1** *(continued)*

Uniform convertor

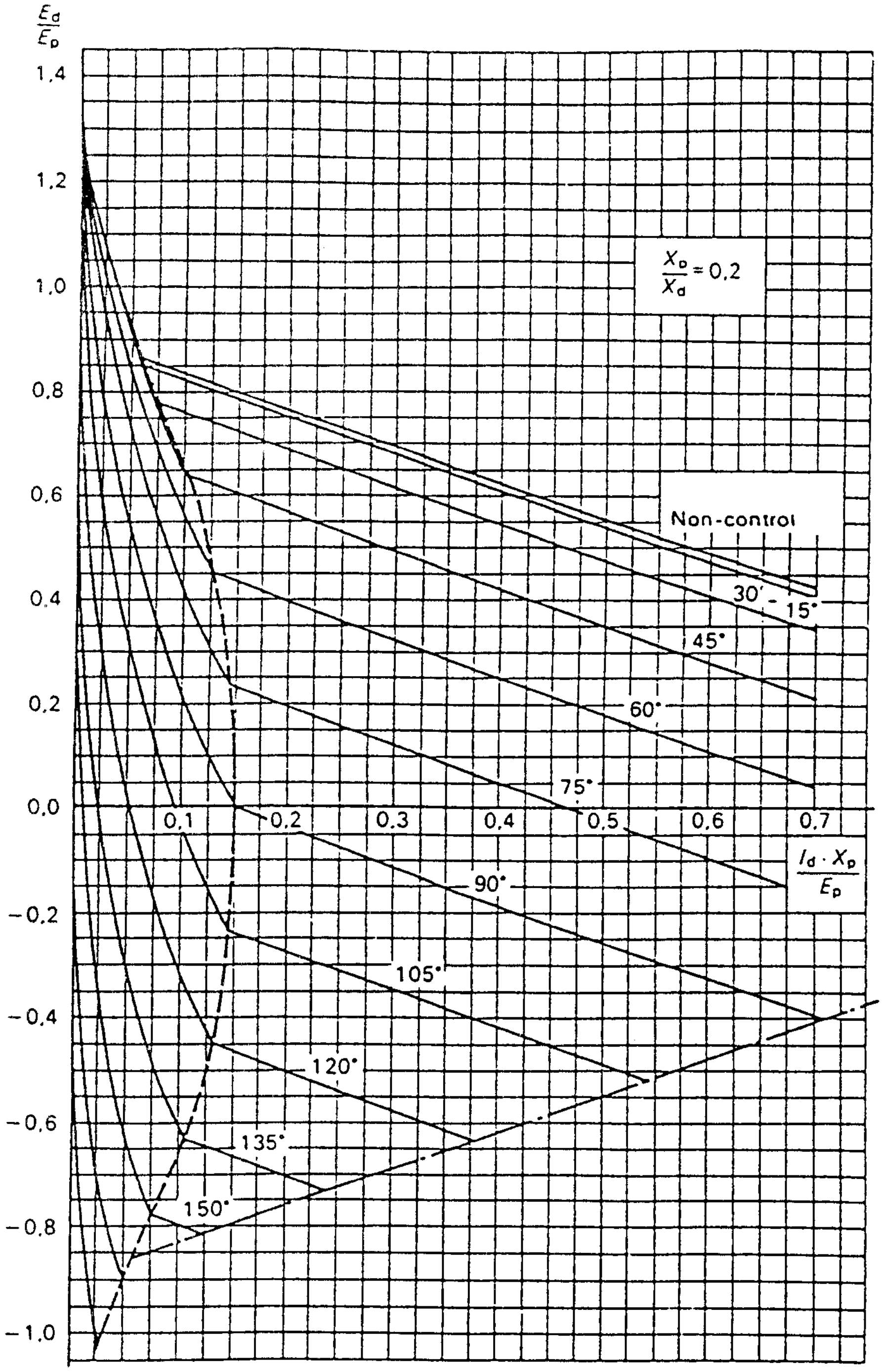


Figure A.1c

**Figure A.1** *(continued)*

Uniform convertor

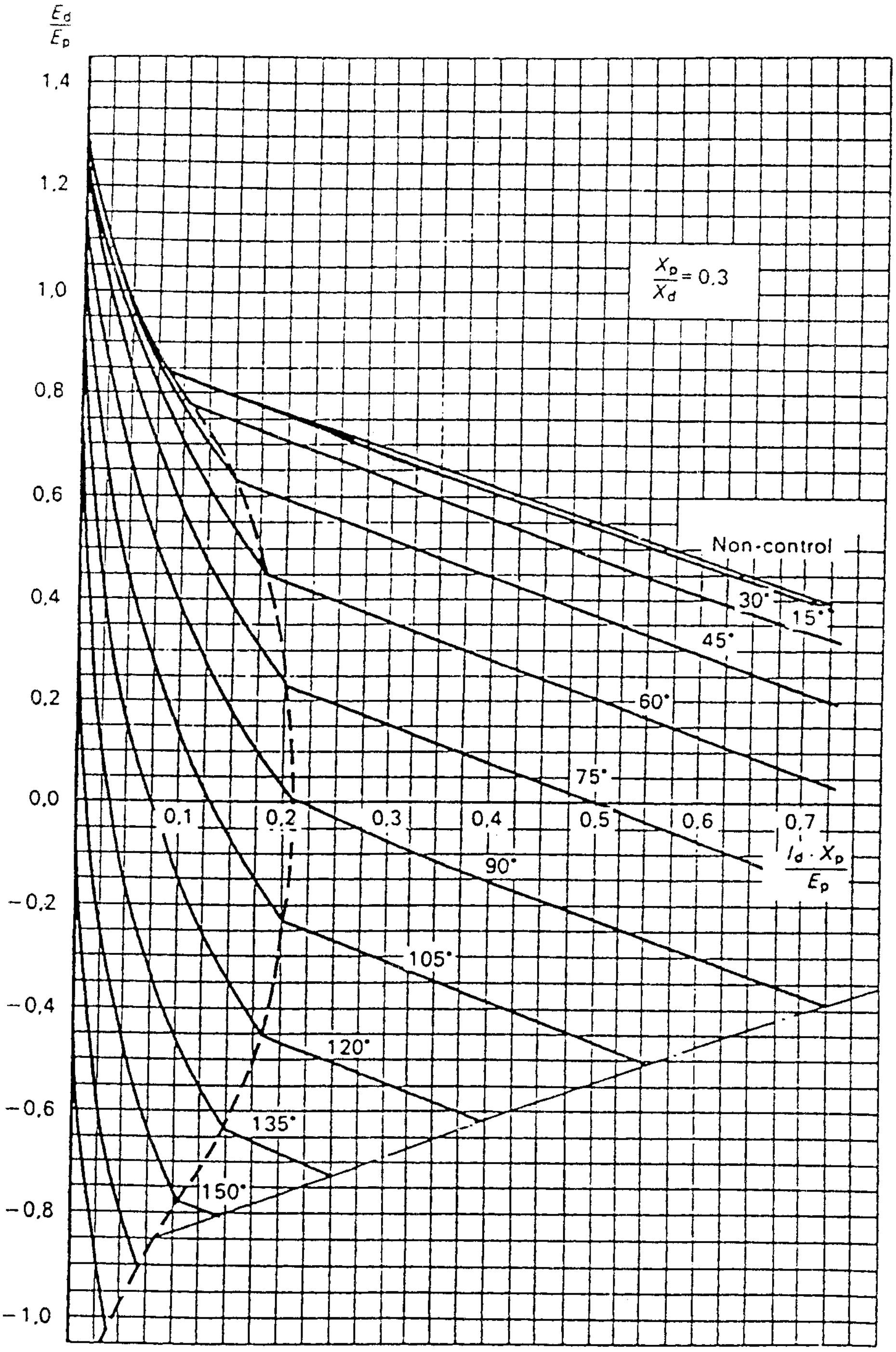


Figure A.1d

**Figure A.1** *(continued)*

Uniform convertor

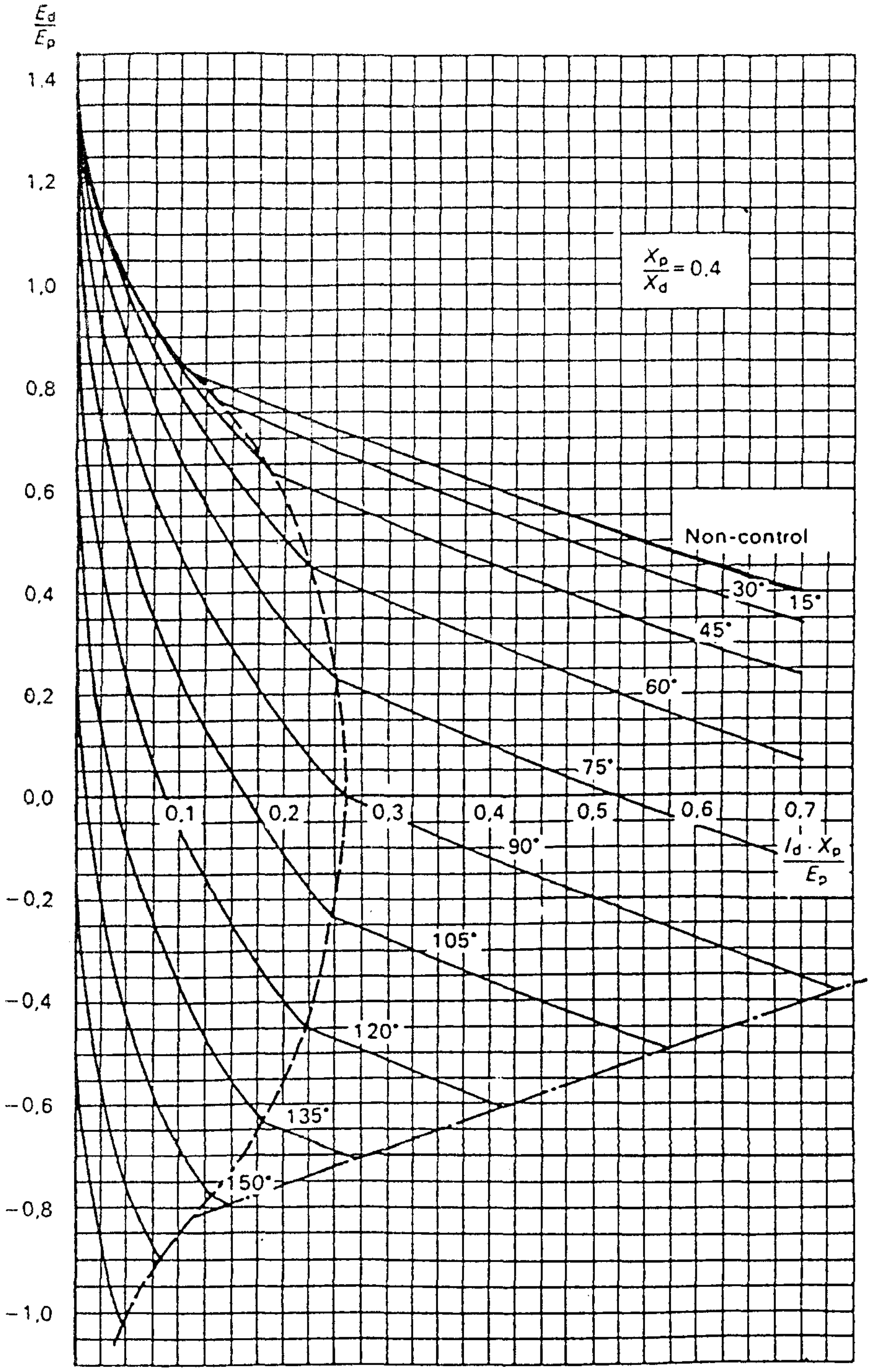


Figure A.1e

**Figure A.1** *(continued)*

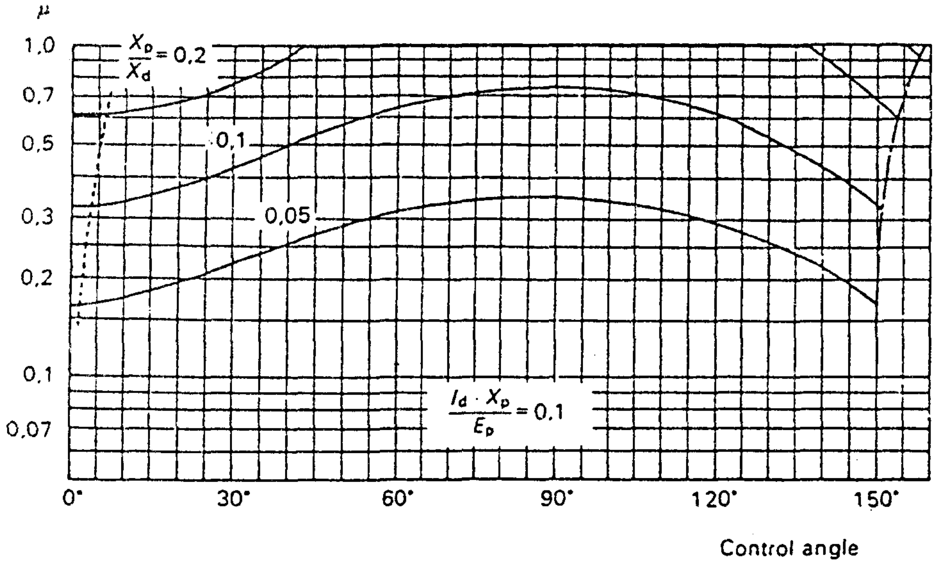


Figure A.2a

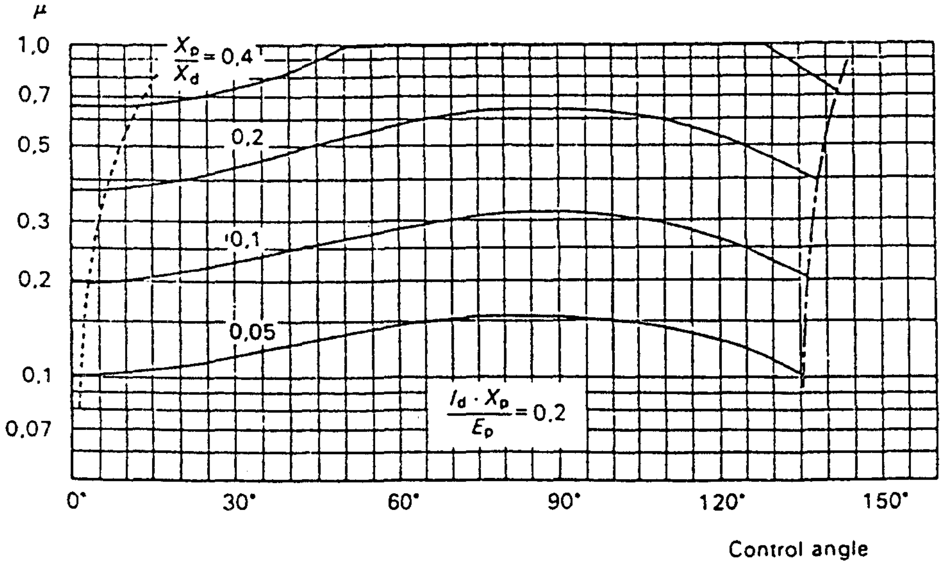


Figure A.2b

**Figure A.2** *(continued)*

Uniform convertor

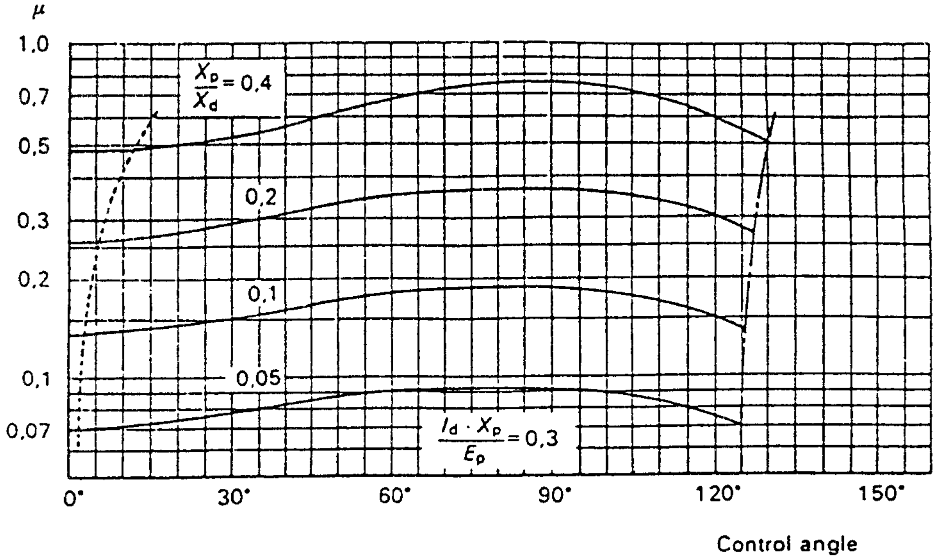


Figure A.2c

**Figure A.4** *(continued)*

Uniform convertor

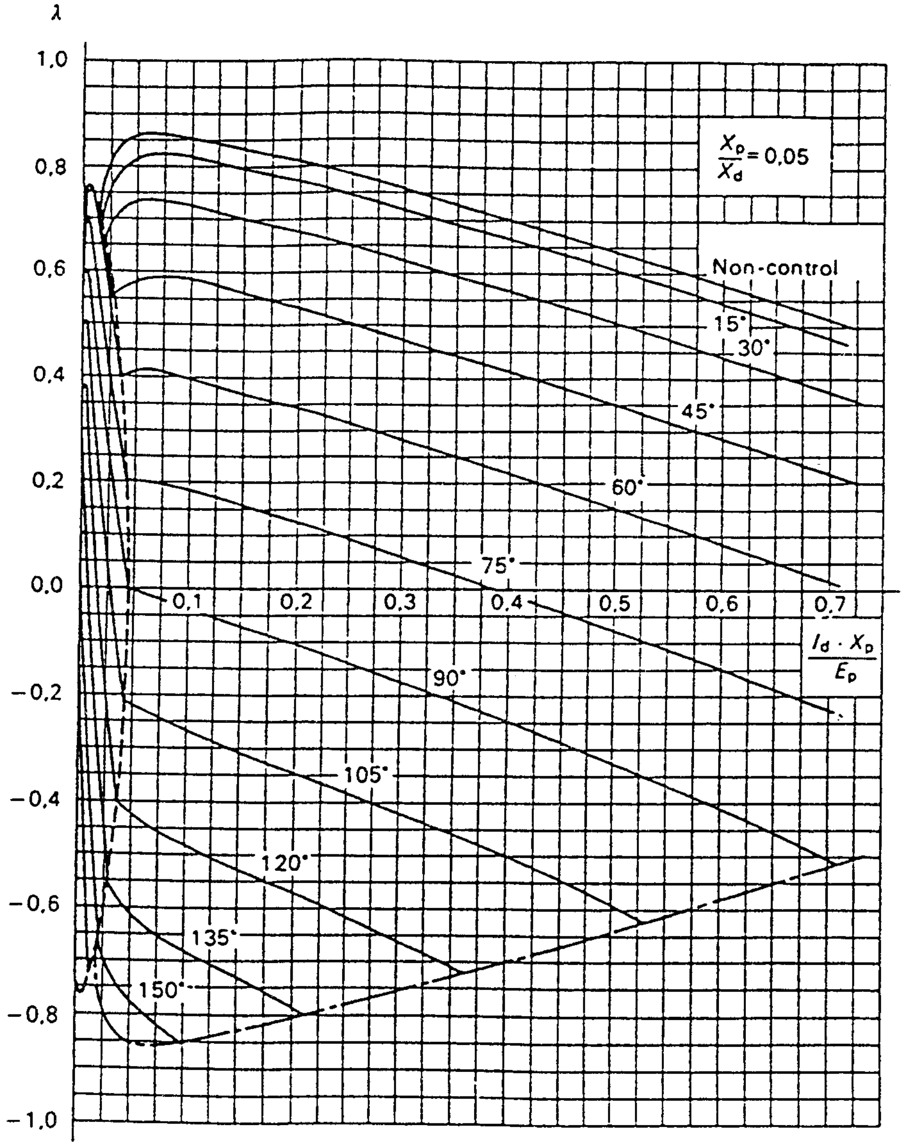


Figure A.3a

Figure A.3 – Total power factor $\lambda$

Uniform convertor

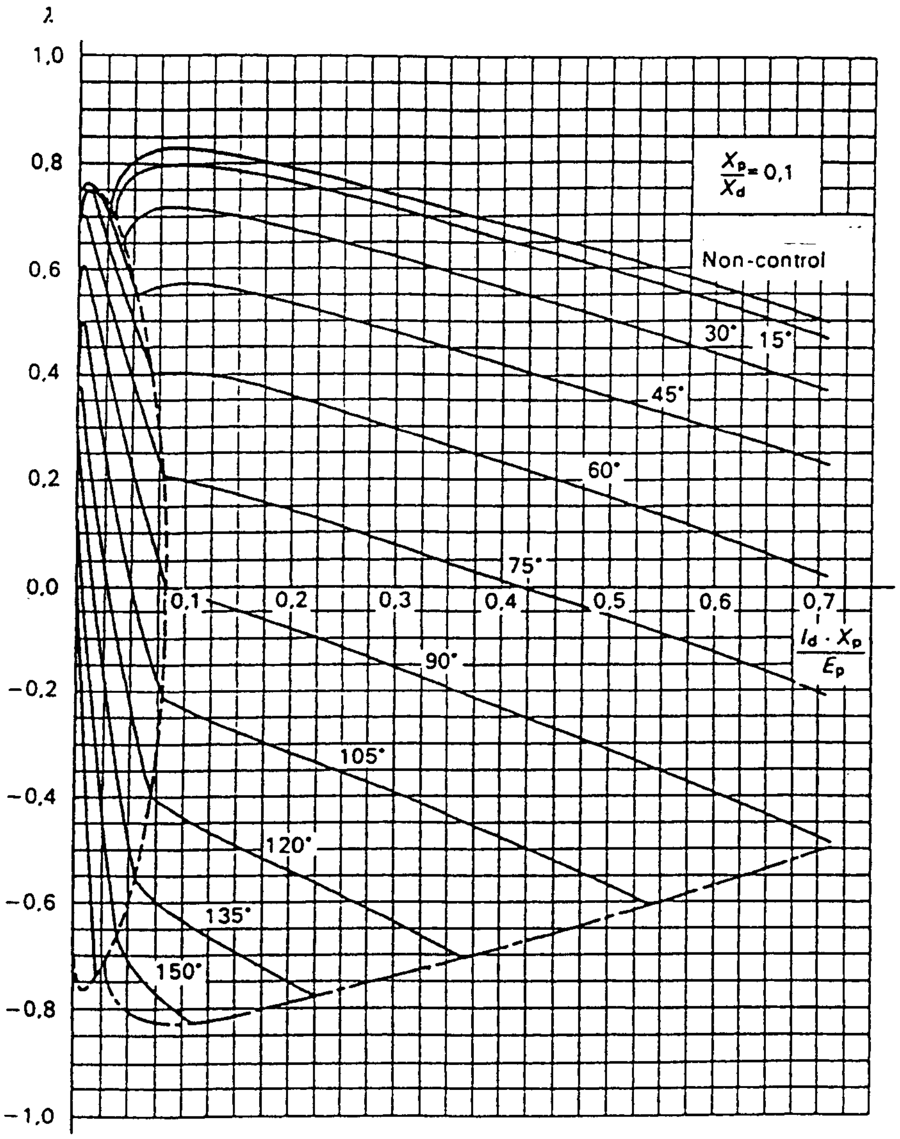


Figure A.3b

**Figure A.3** *(continued)*

Uniform convertor

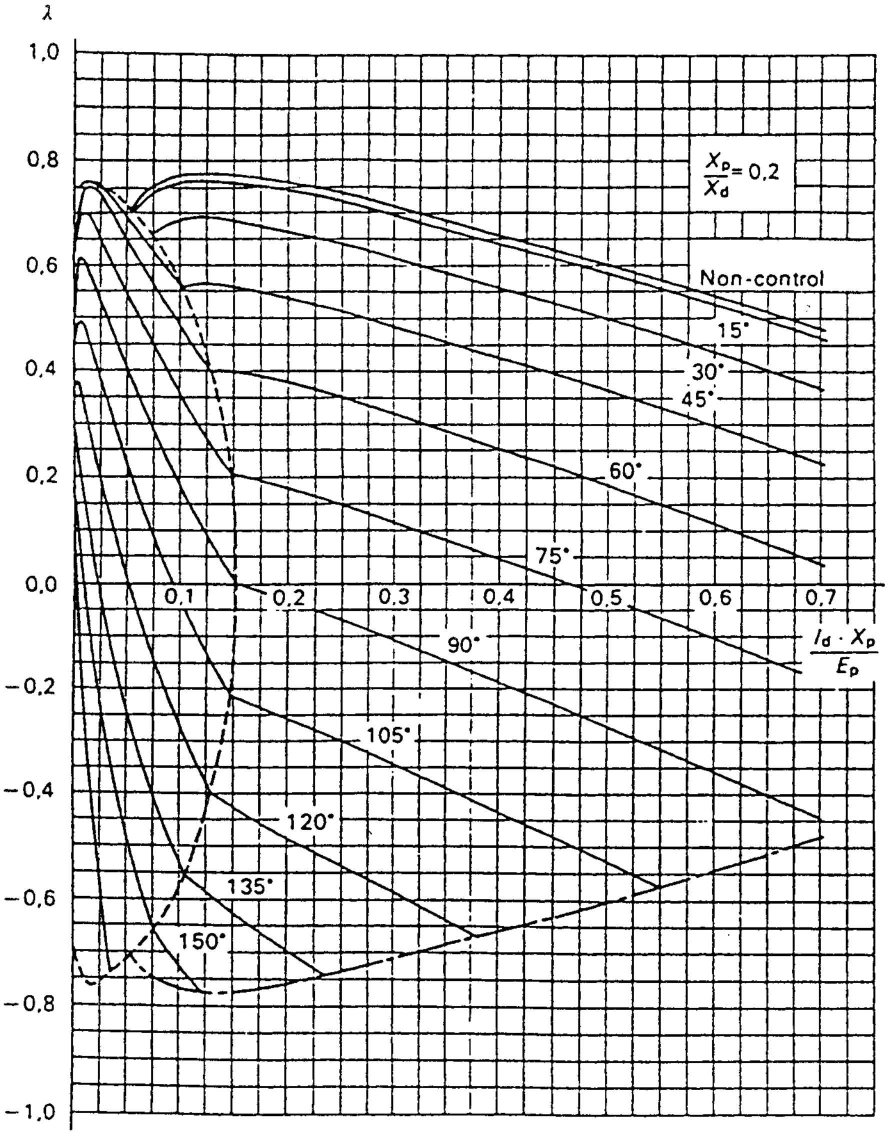


Figure A.3c

**Figure A.3** *(continued)*

Uniform convertor

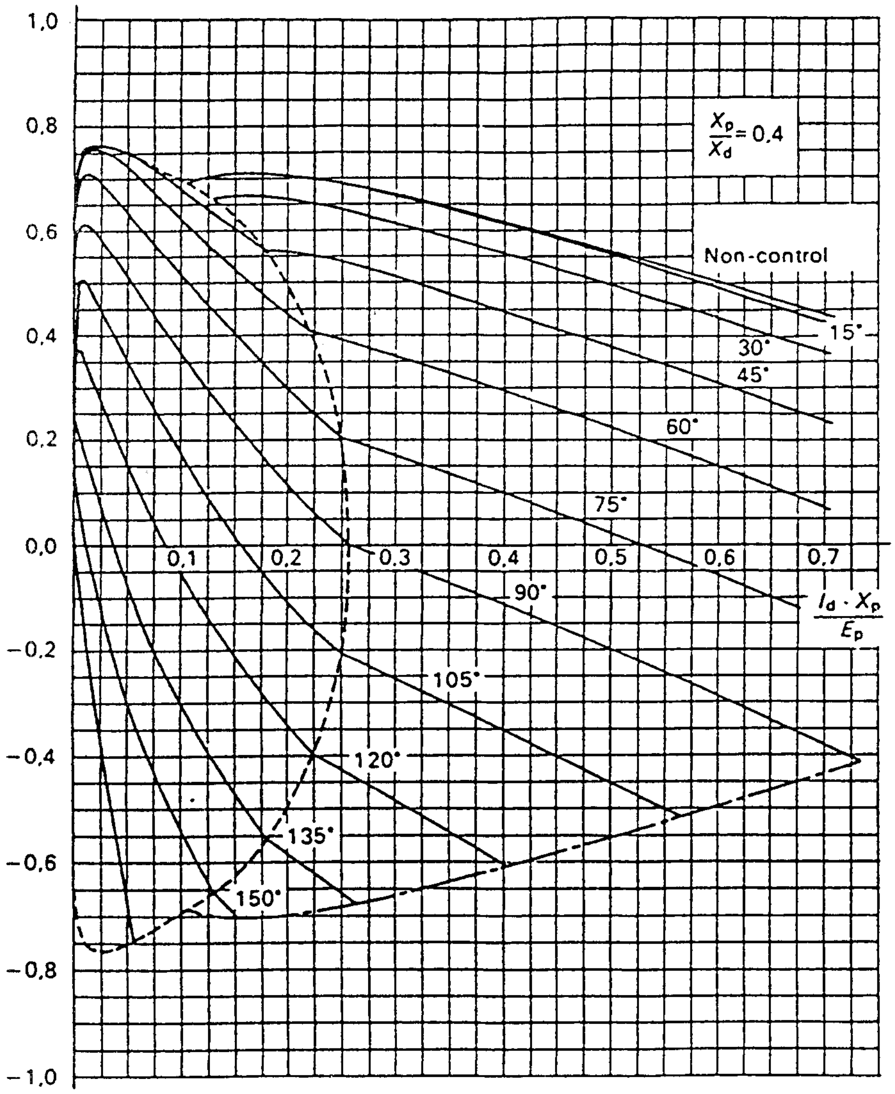


Figure A.3d

**Figure A.3** *(continued)*

Uniform convertor

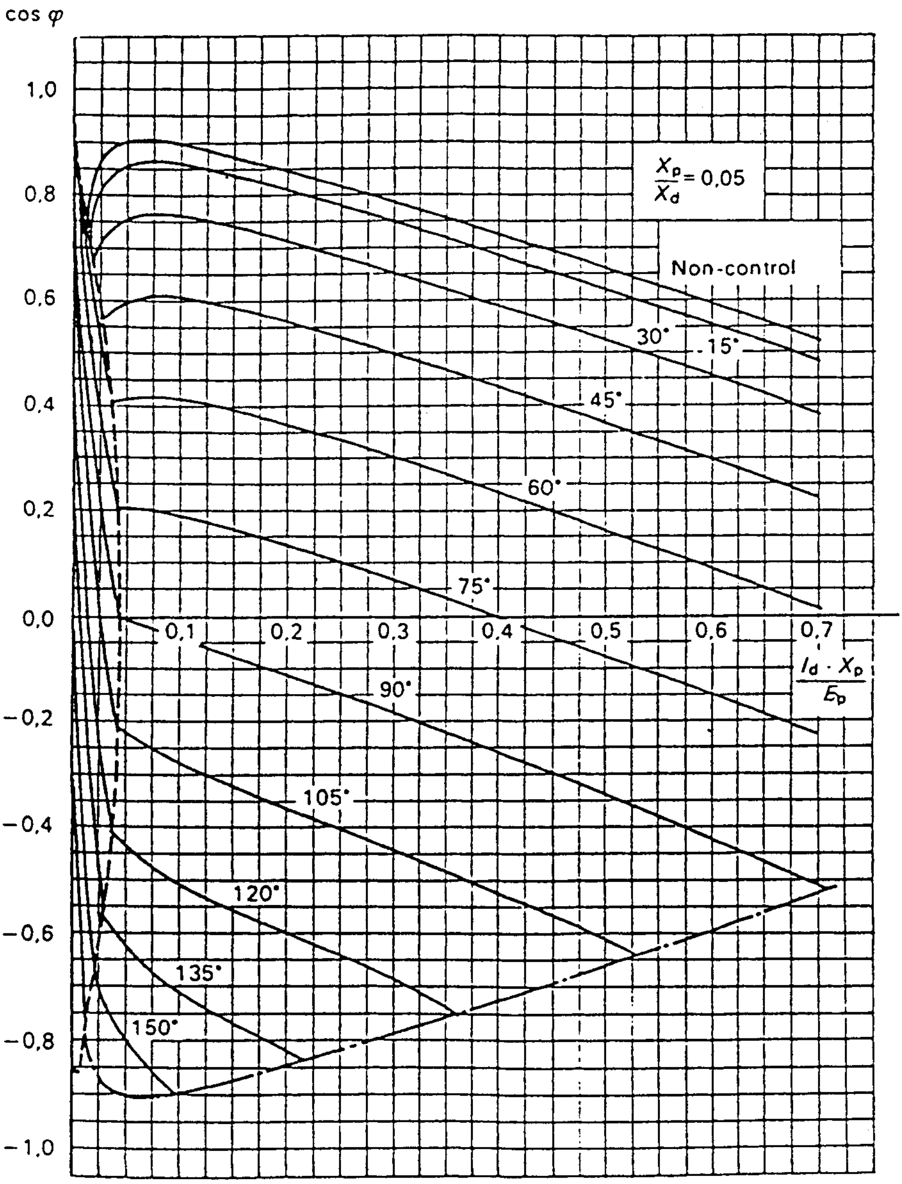


Figure A.4a

Figure A.4 – Displacement factor cos φ

Uniform convertor

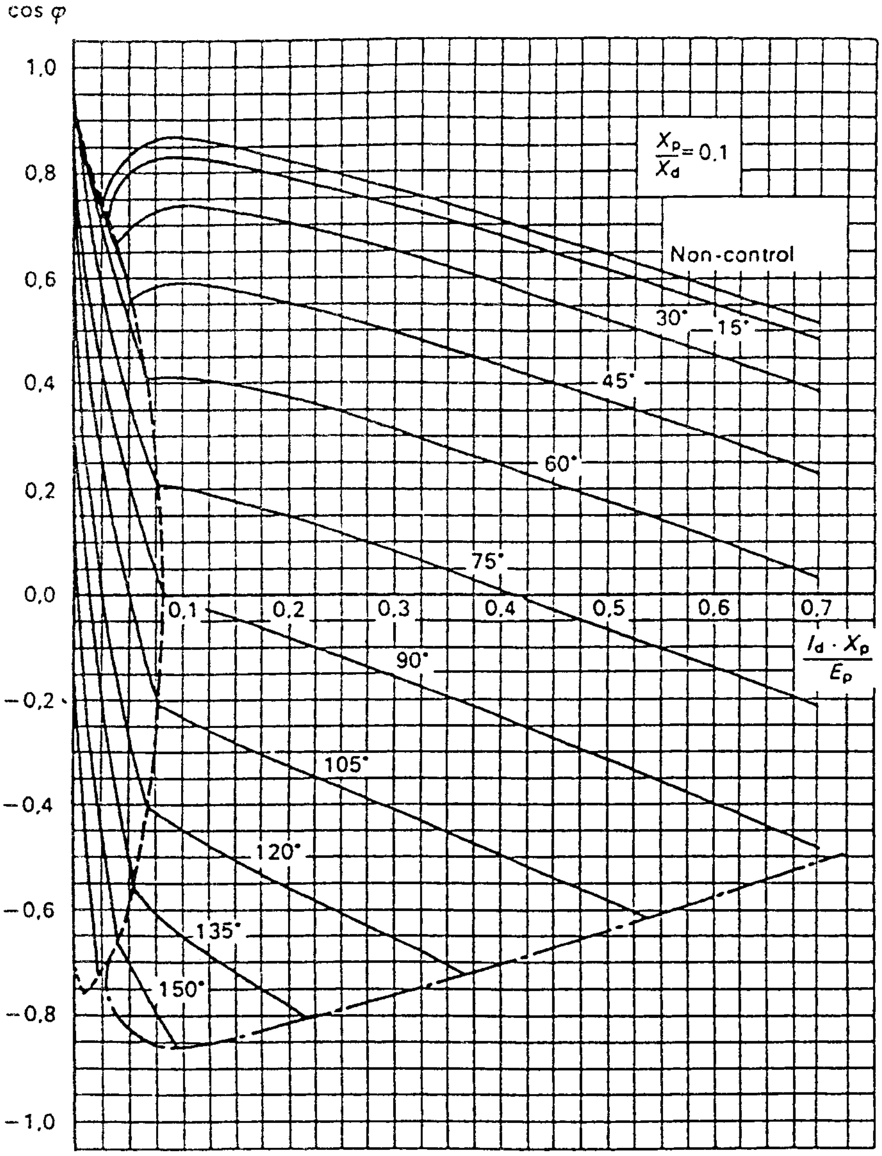


Figure A.4b

Figure A.4 *(continued)*

Uniform convertor

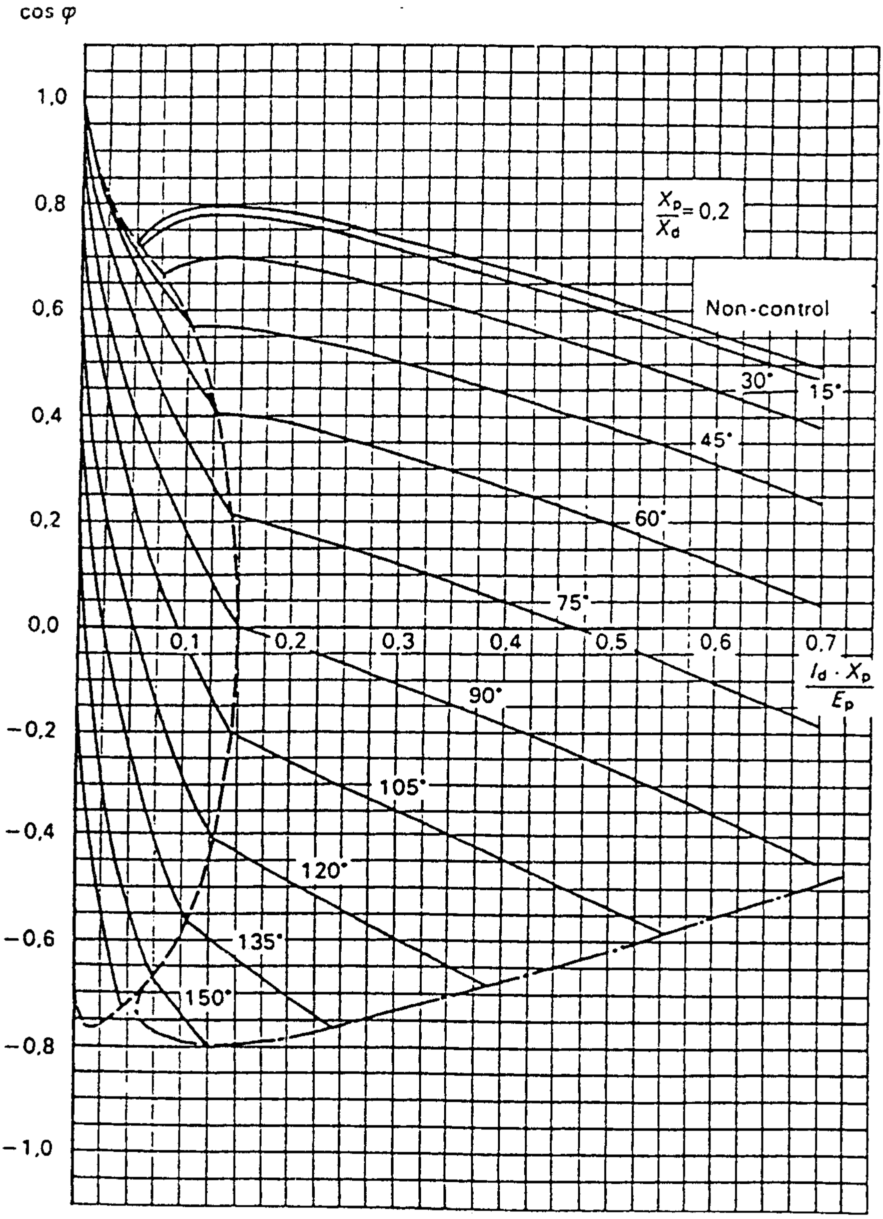


Figure A.4c

**Figure A.4** *(continued)*

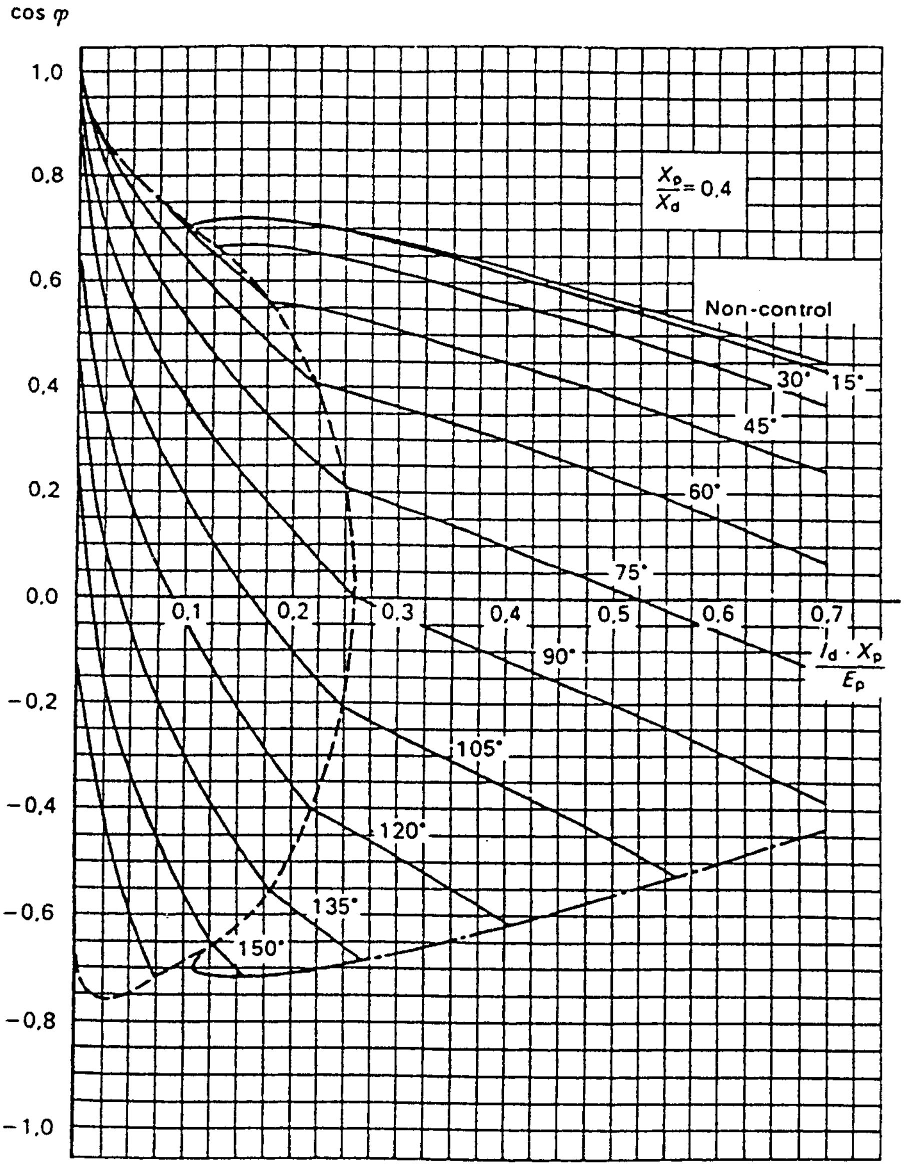


Figure A.4d

Figure A.4 *(continued)*

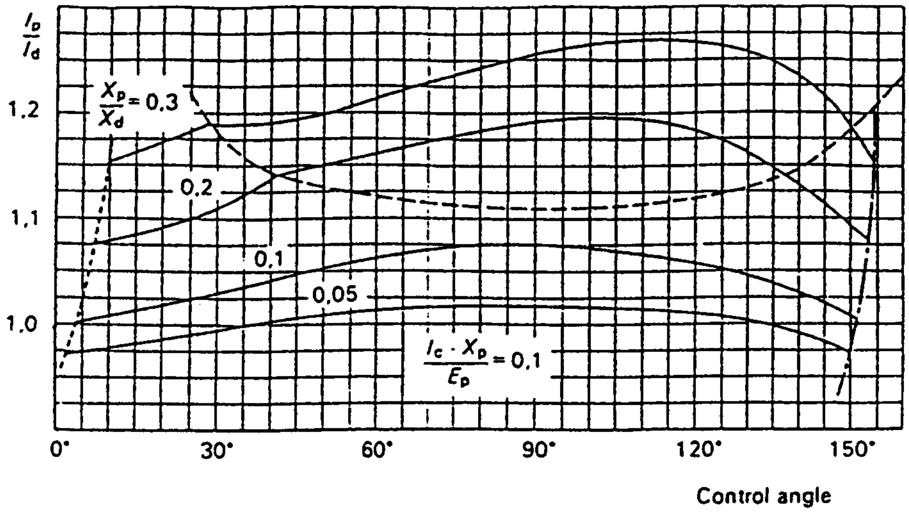


Figure A.5a

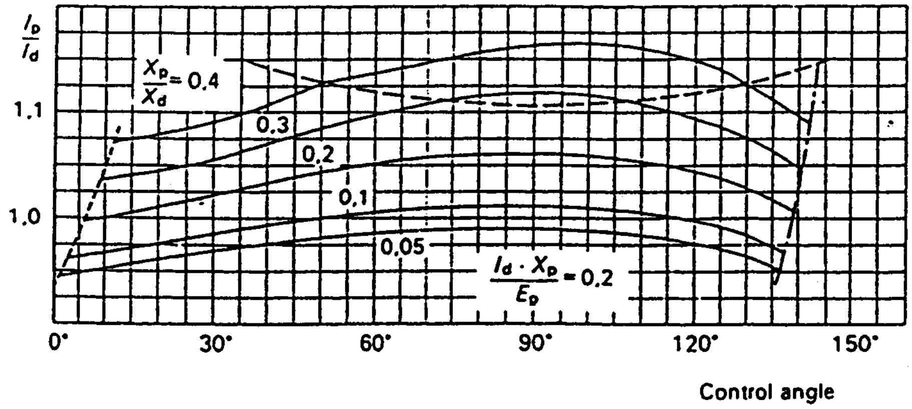


Figure A.5b

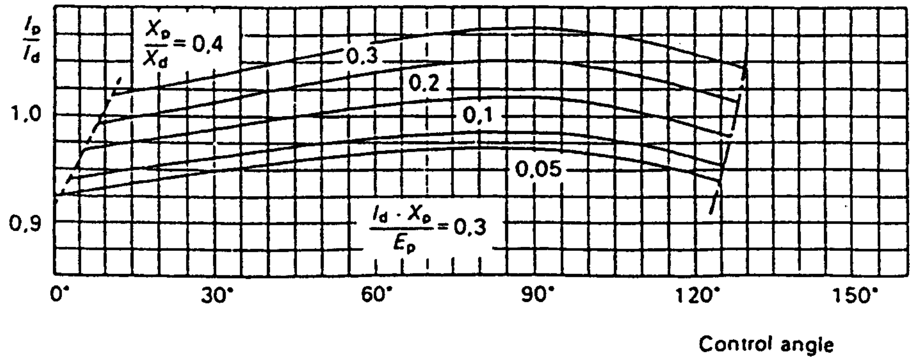


Figure A.5c

Figure A.5 – RMS value of a.c. side current

Uniform convertors

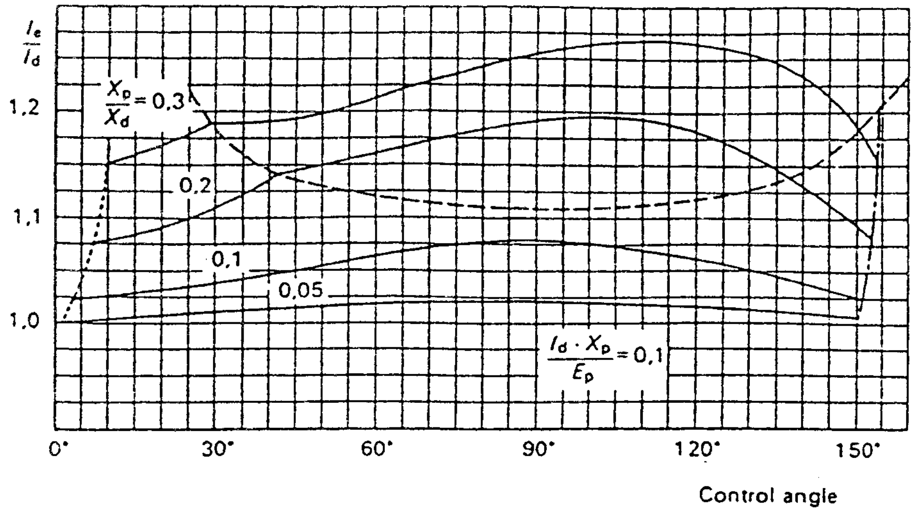


Figure A.6a

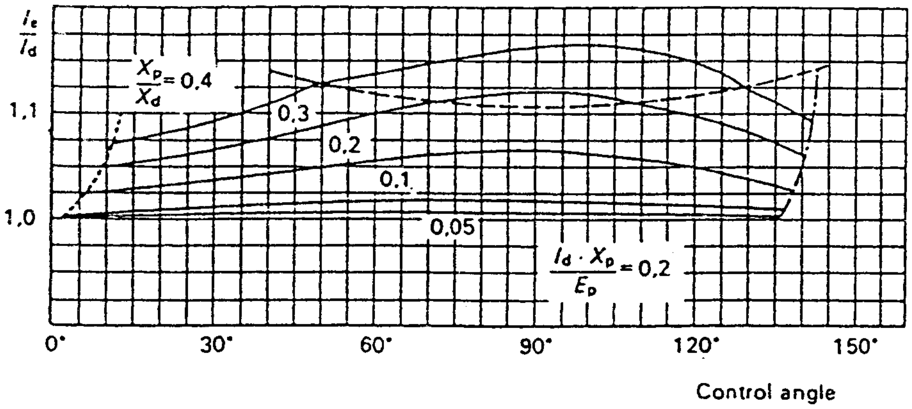


Figure A.6b

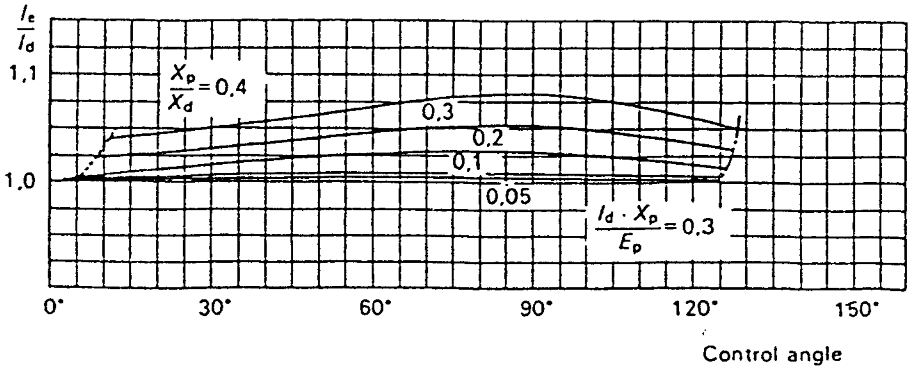


Figure A.6c

Figure A.6 – RMS value of d.c. side current

Non-uniform convertor

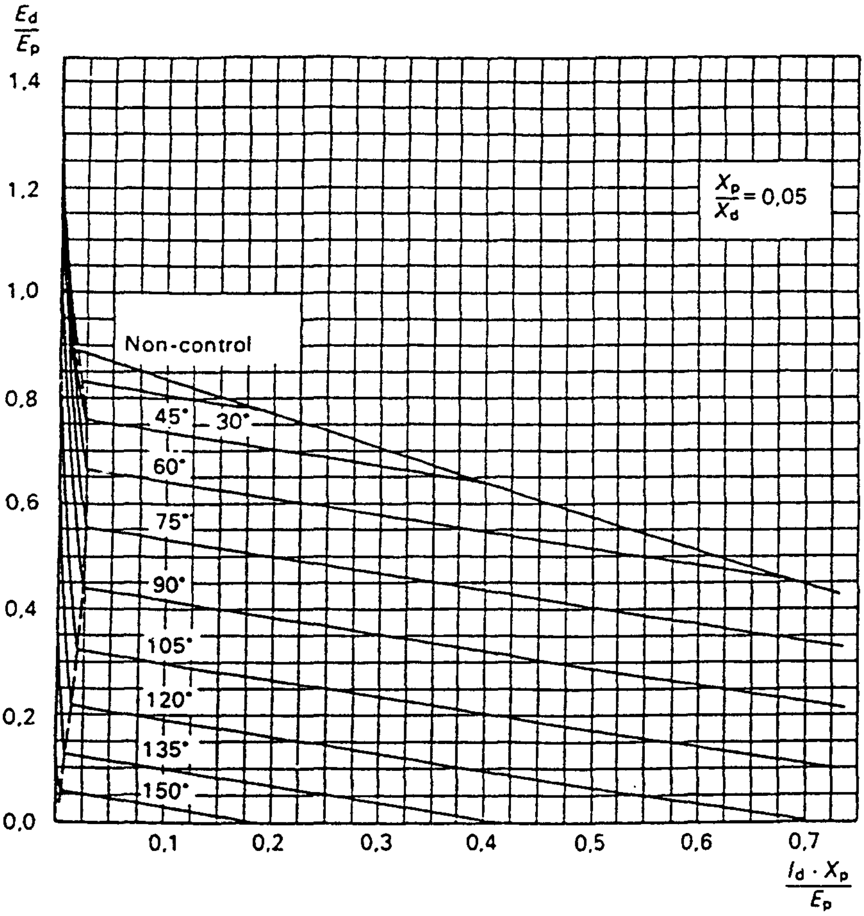


Figure A.7a

**Figure A.7 – DC voltage regulation**

Non-uniform convertor

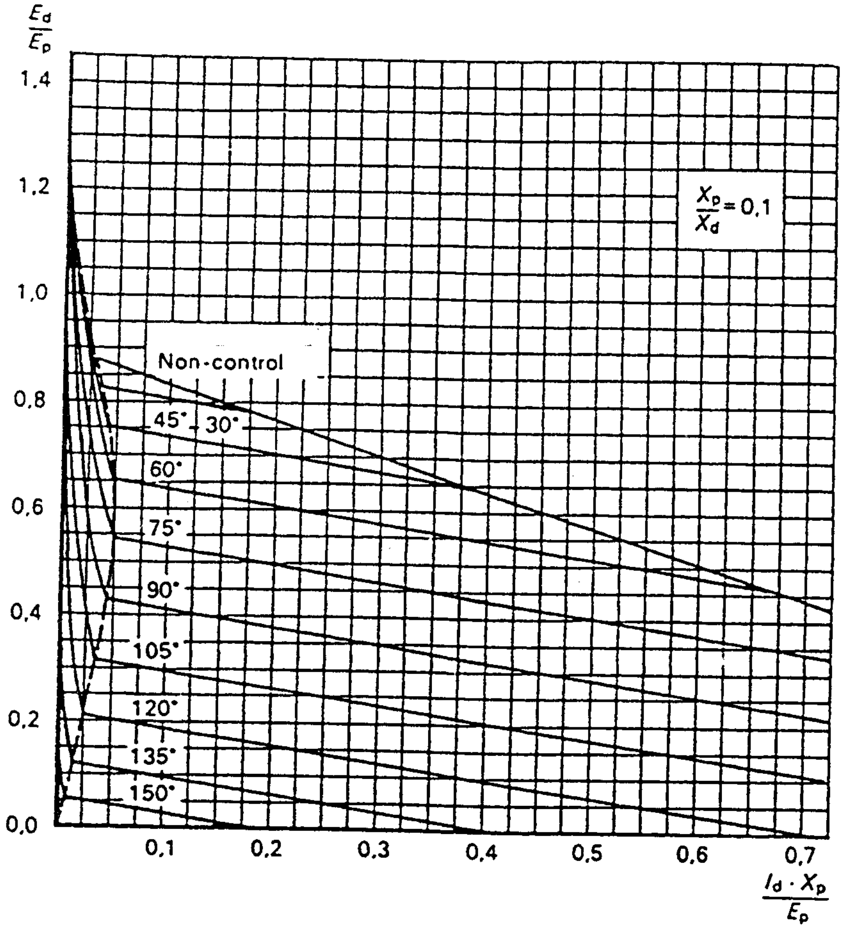


Figure A.7b

Figure A.7 *(continued)*

Non-uniform convertor

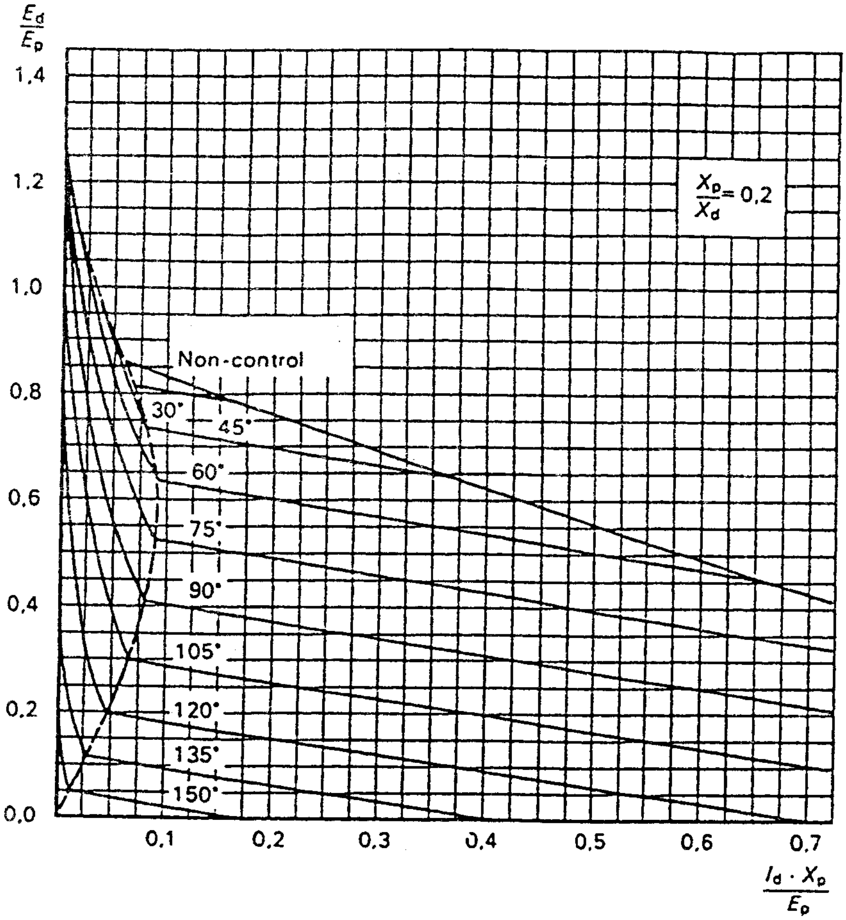


Figure A.7c

Figure A.7 *(continued)*

Non-uniform convertor

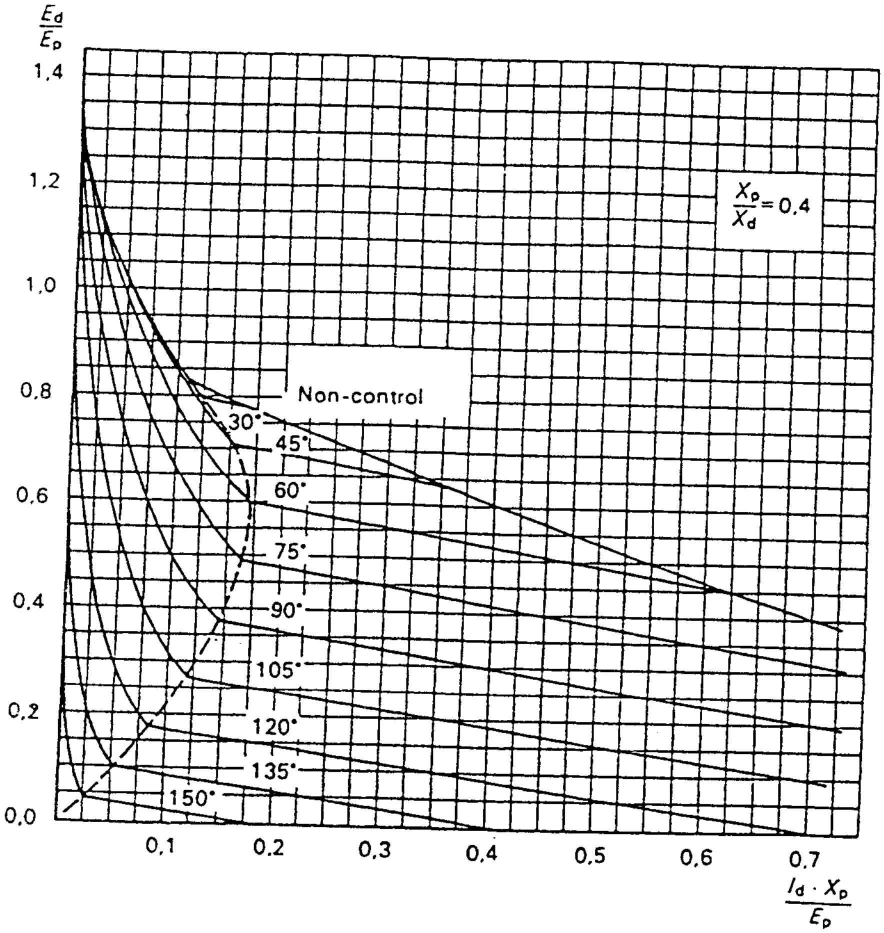


Figure A.7d

Figure A.7 *(continued)*

Non-uniform convertor

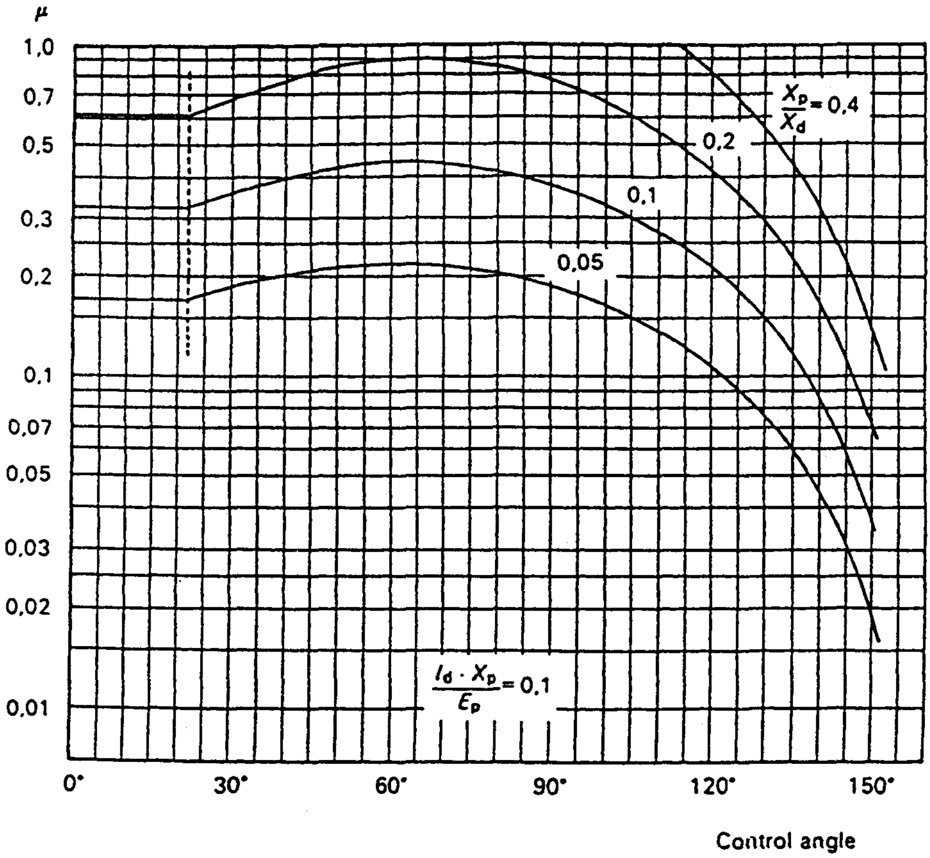


Figure A.8a

Figure A.8 – Ripple factor $\mu$

Non-uniform convertor

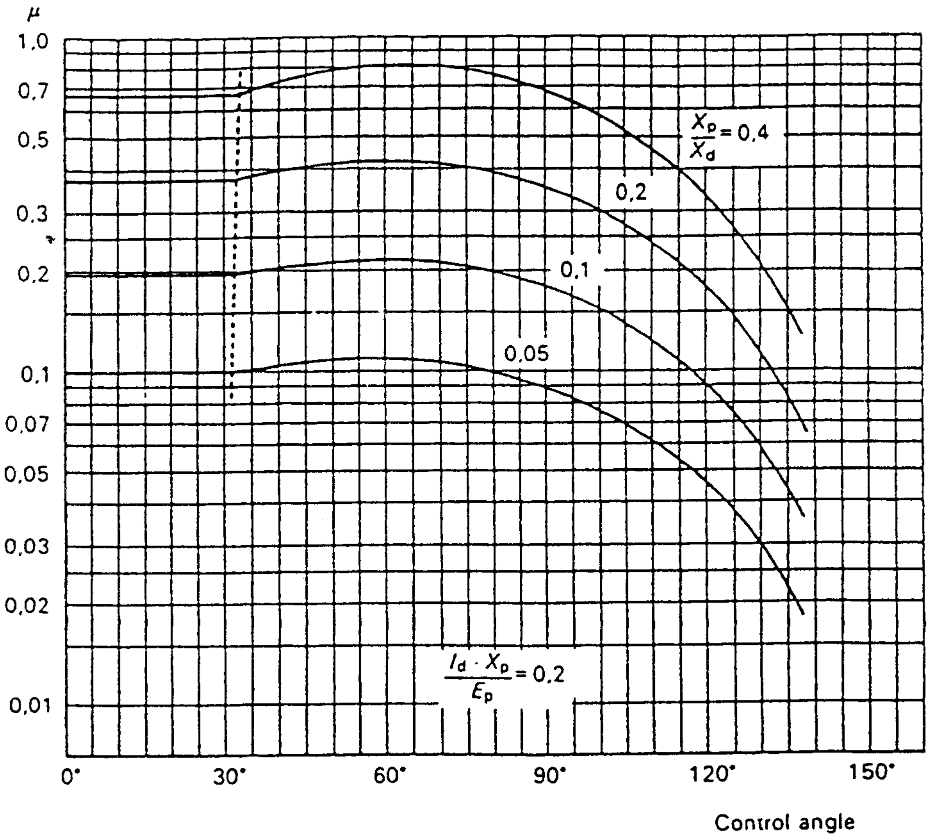


Figure A.8b

Figure A.8 *(continued)*

Non-uniform convertor

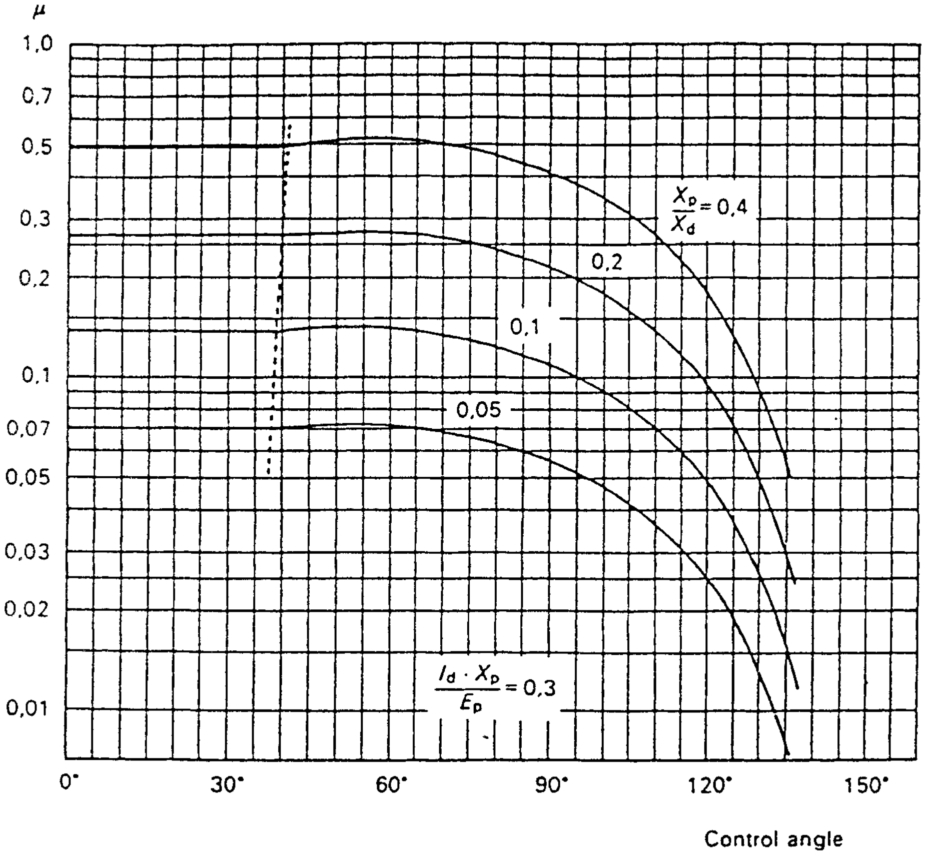


**Figure A.8c**

**Figure A.8** *(continued)*

Non-uniform convertors

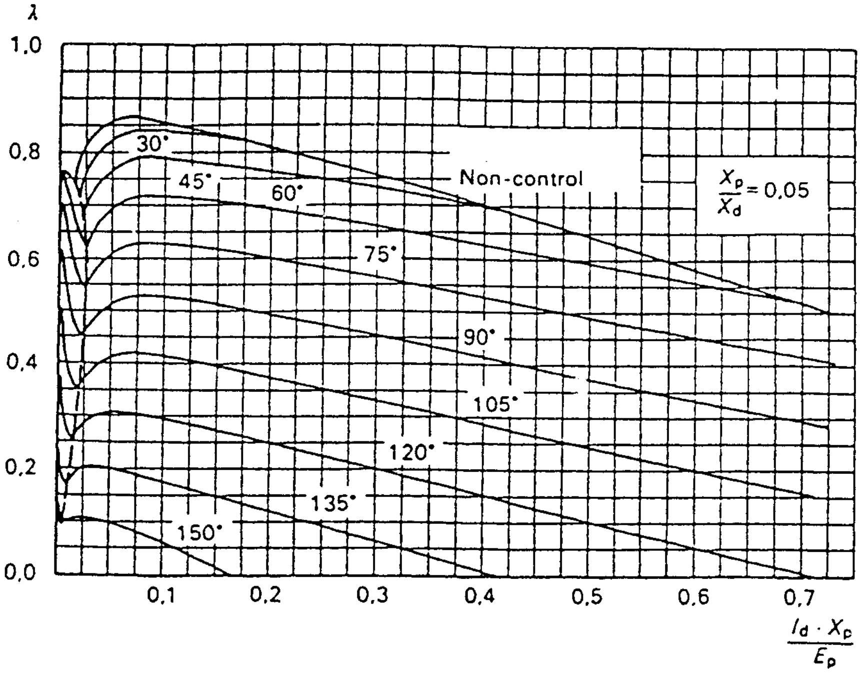


**Figure A.9a**

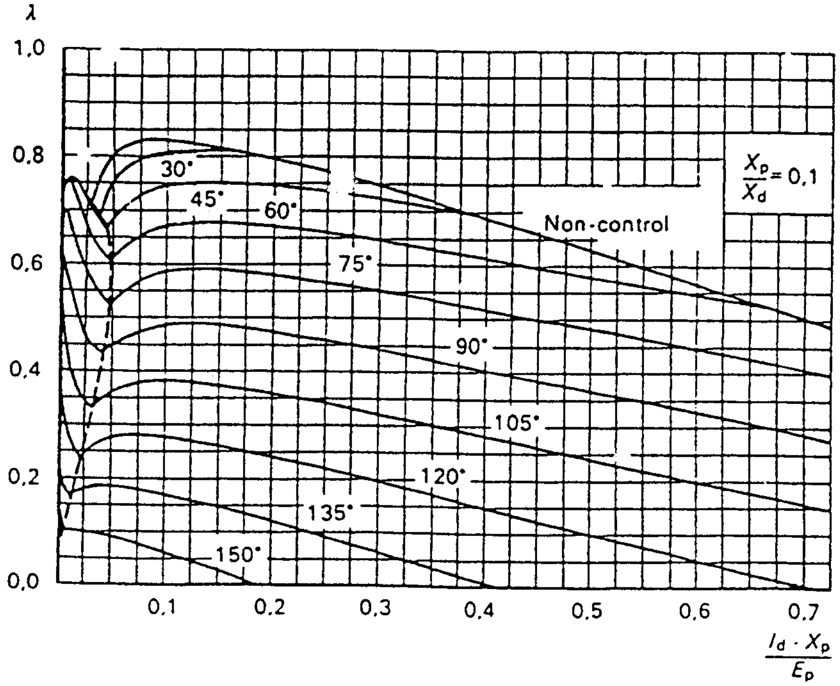


**Figure A.9b**

**Figure A.9 – Total power factor λ**

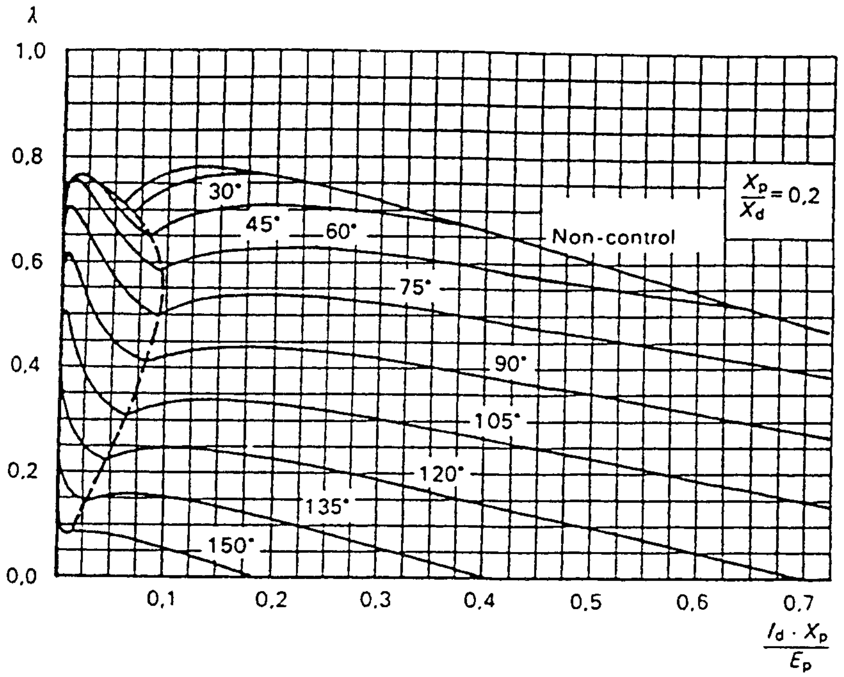


Figure A.9c

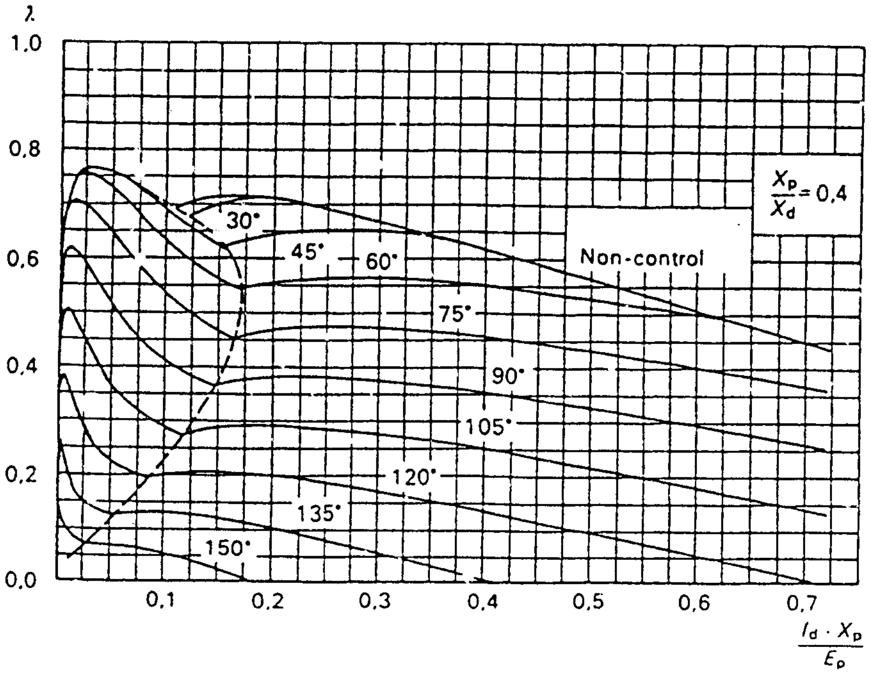


Figure A.9d

Figure A.9 *(continued)*

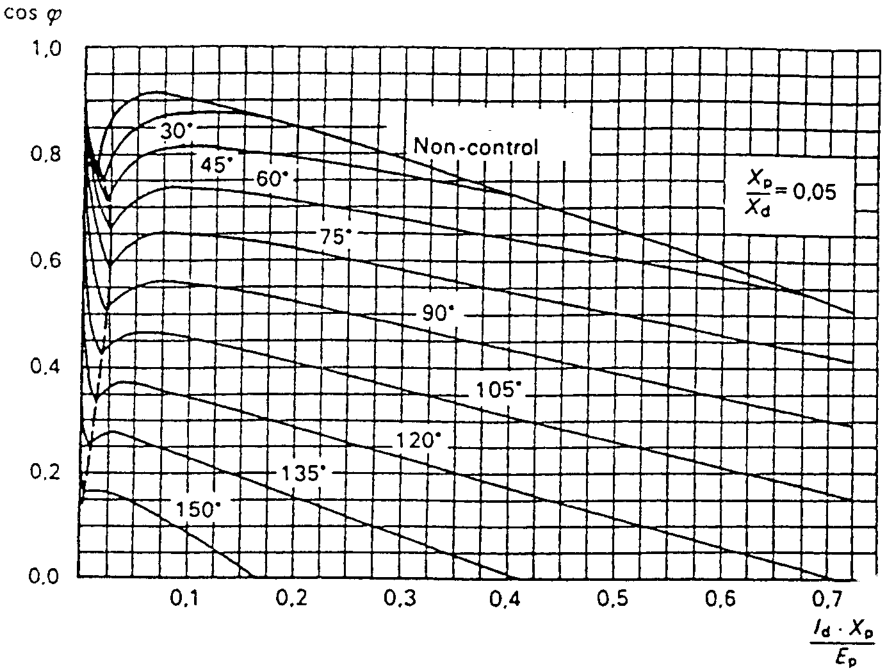


Figure A.10a

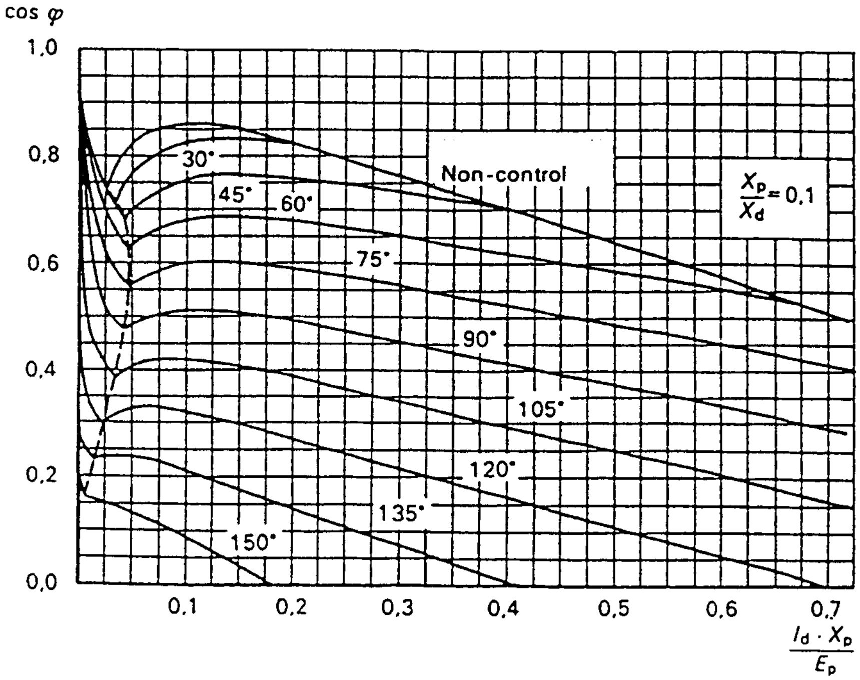


Figure A.10b

Figure A.10 – Displacement factor cos $\varphi$

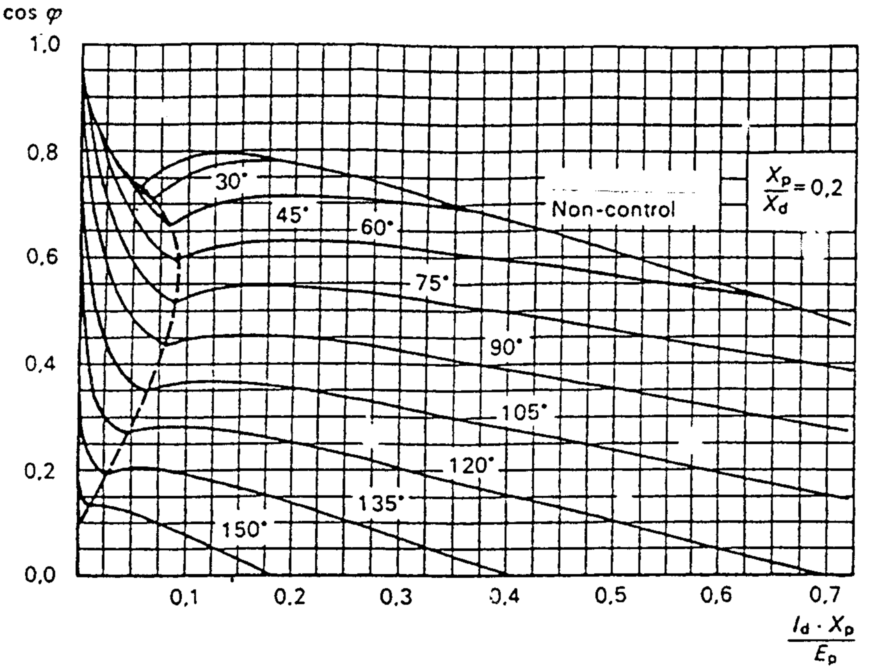


Figure A.10c

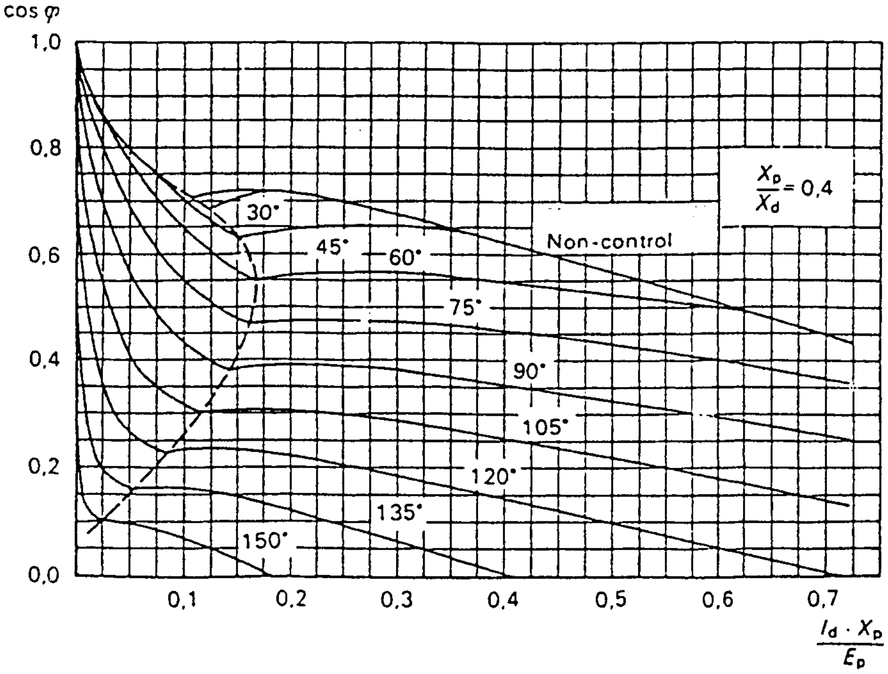
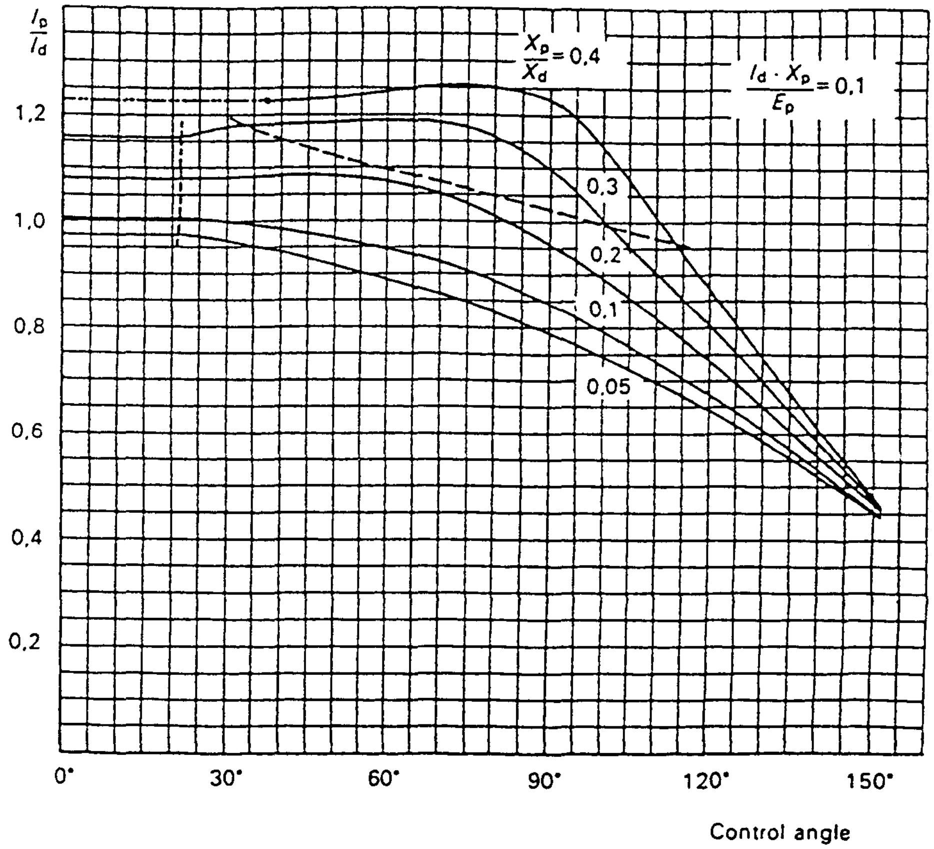


Figure A.10d

**Figure A.10** *(continued)*

Non-uniform convertor



The characteristics along this line are obtained if the control pulse is wide enough, but do not exist if it is not.

Figure A.11a

**Figure A.11 – RMS value of a.c. side current**

Non-uniform convertor

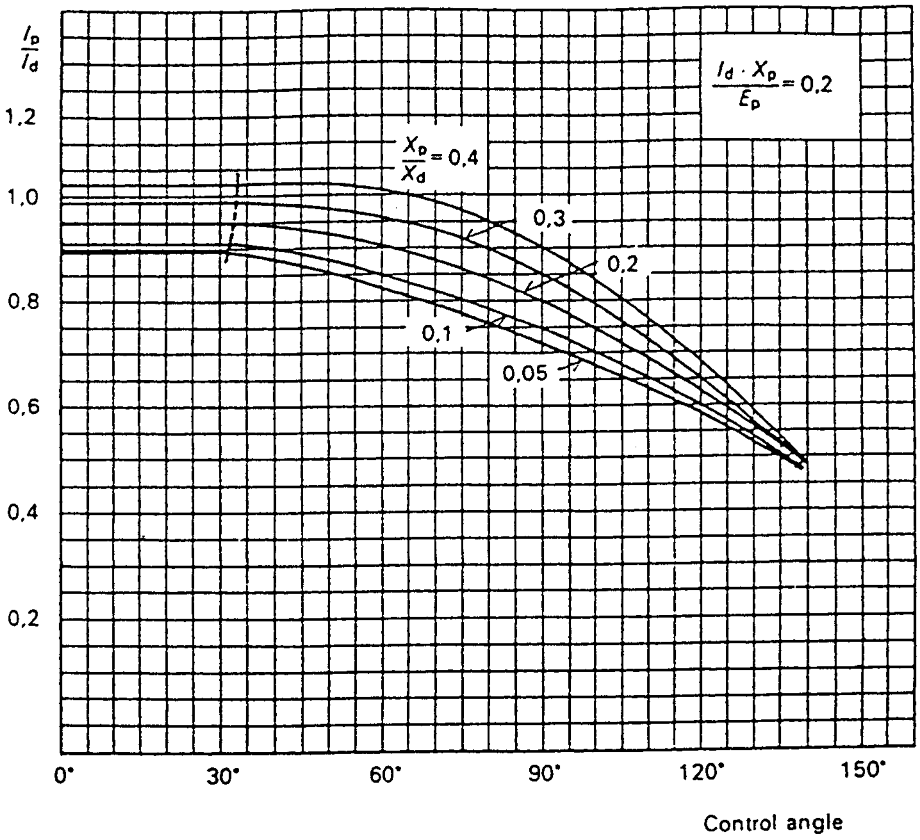


**Figure A.11b**

**Figure A.11** *(continued)*

Non-uniform convertor

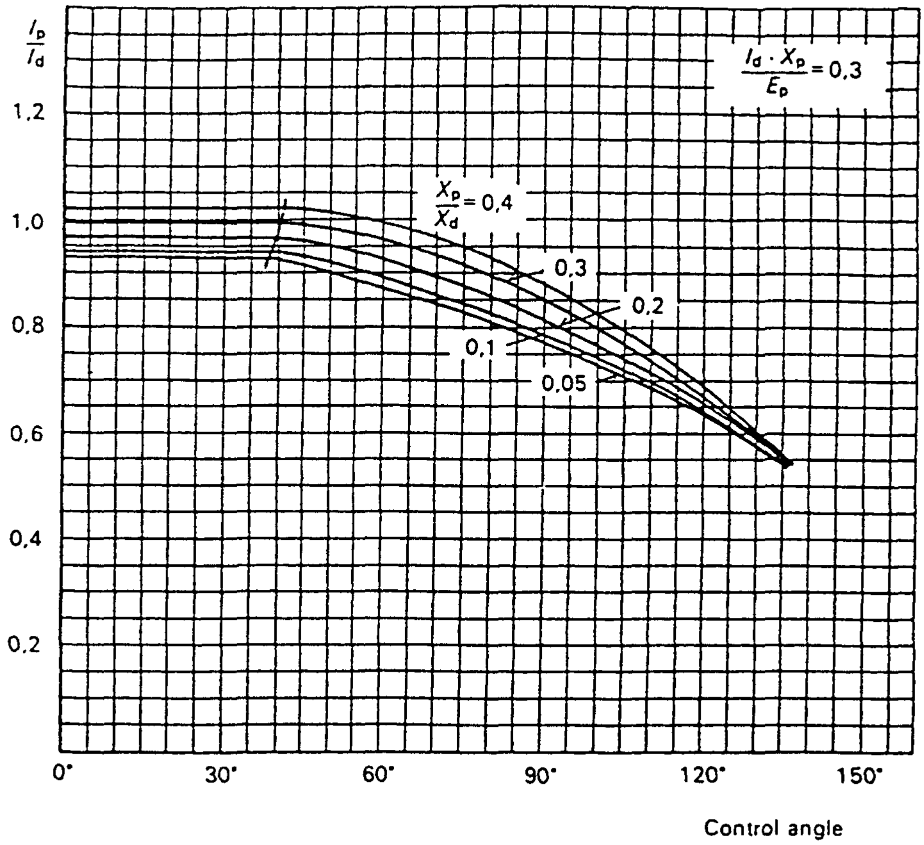


Figure A.11c

Figure A.11 *(continued)*

Non-uniform convertor

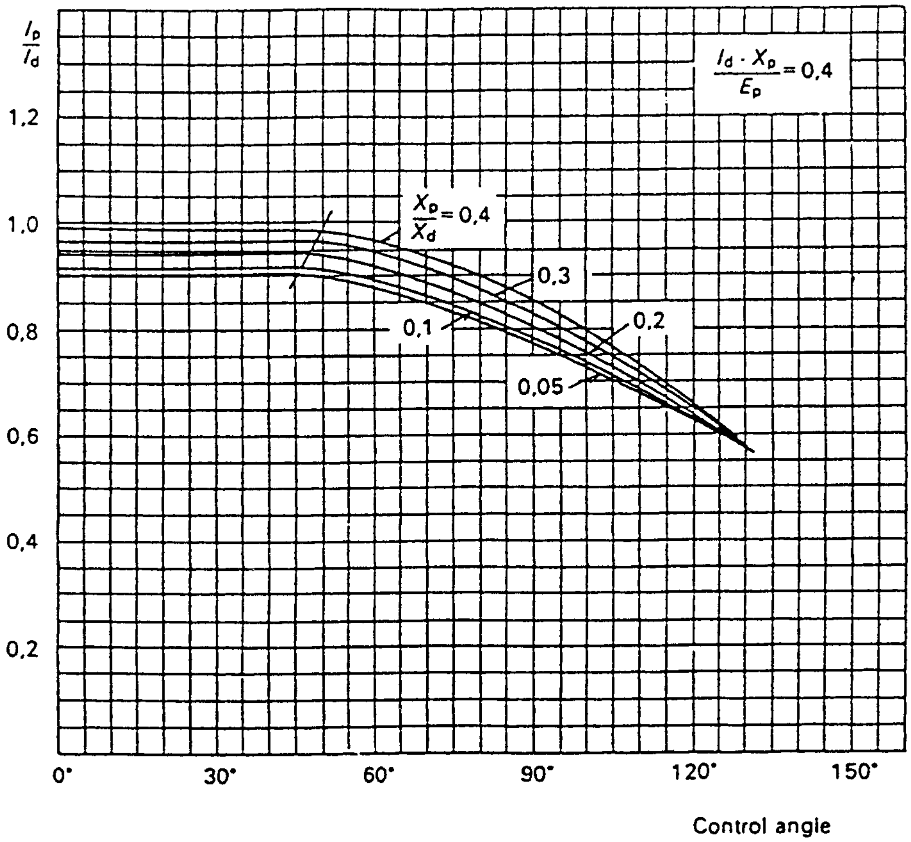


Figure A.11d

**Figure A.11** *(continued)*

Non-uniform convertor

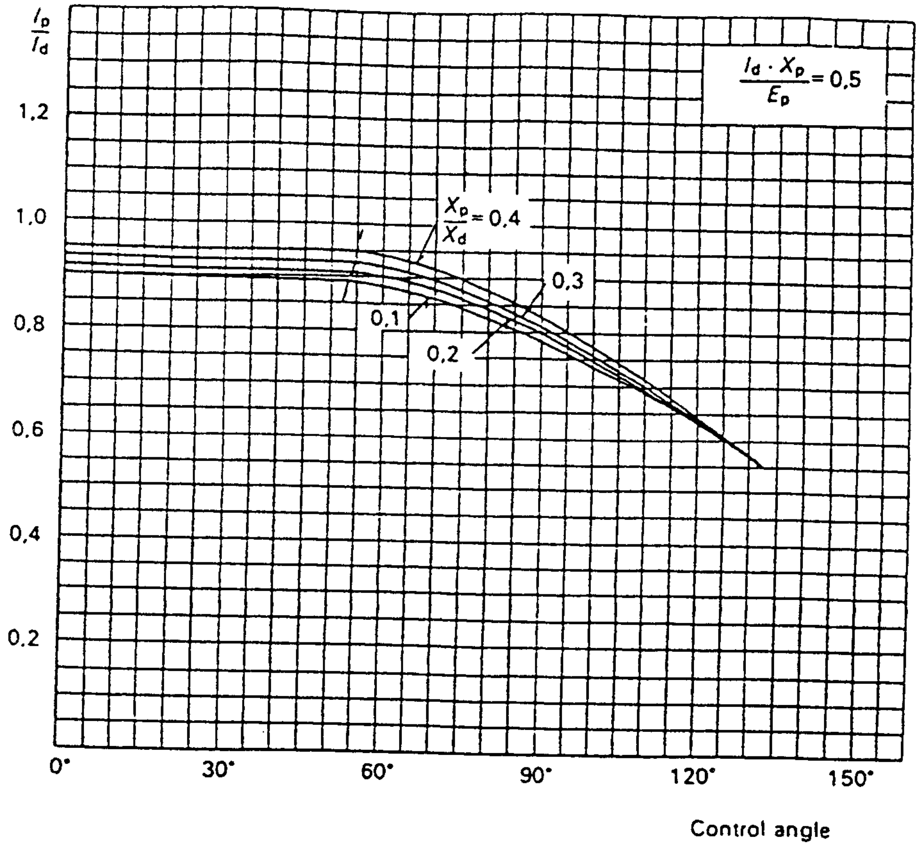


Figure A.11e

**Figure A.11** *(continued)*

Non-uniform convertor

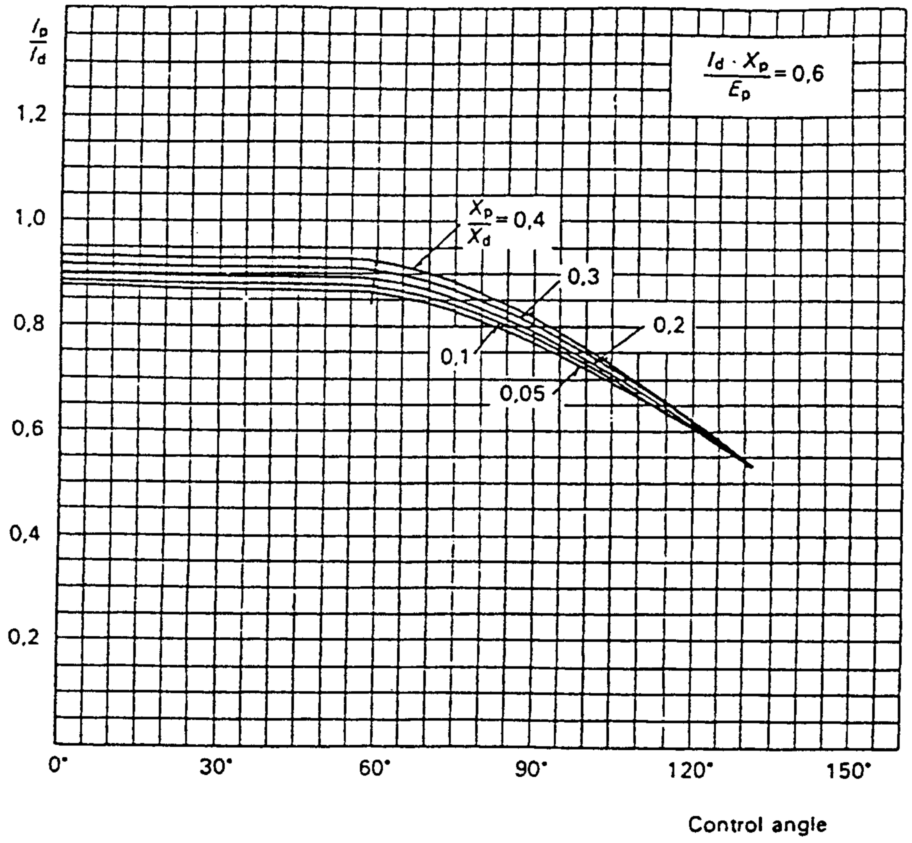


Figure A.11f

**Figure A.11** *(continued)*

Non-uniform convertor

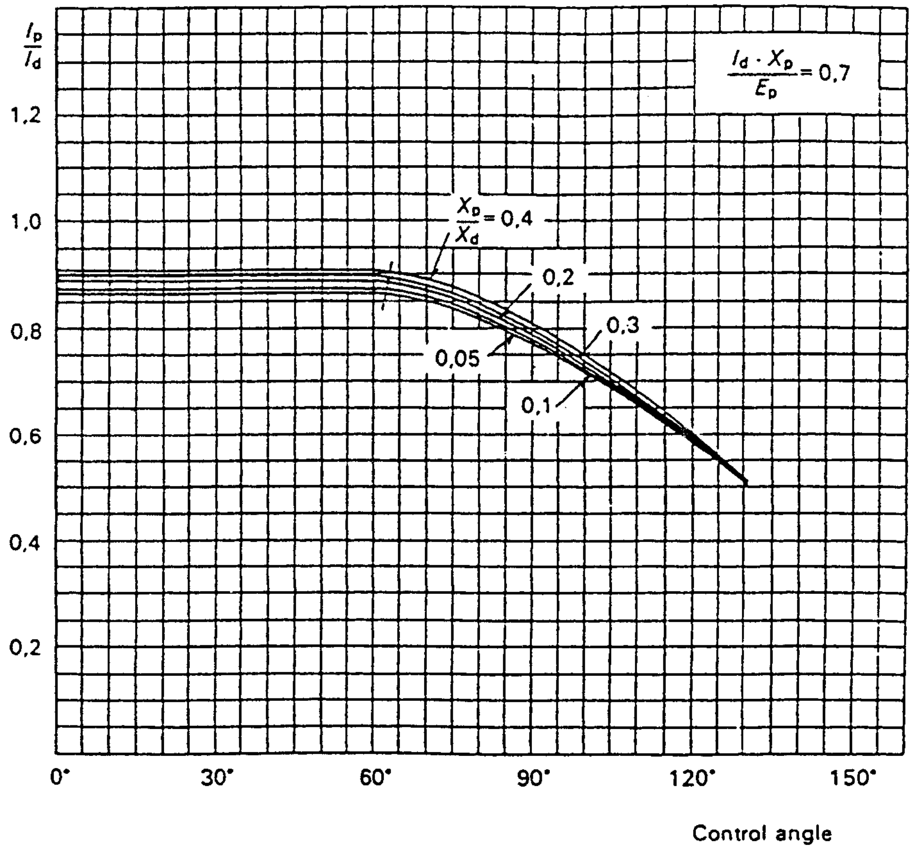


Figure A.11g

Figure A.11 *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 27

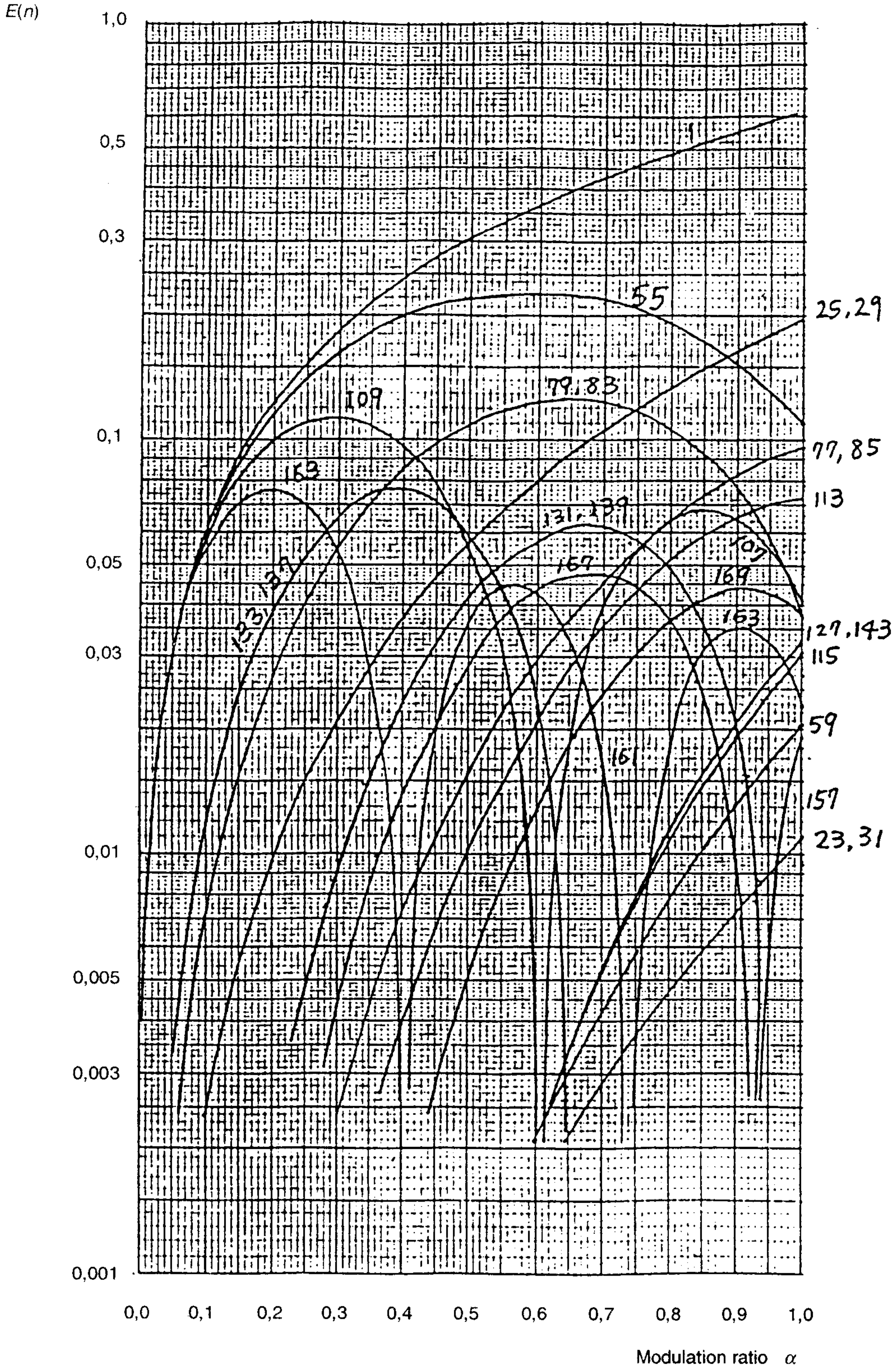


Figure A.12a

Figure A.12 – Harmonic output voltage

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 27

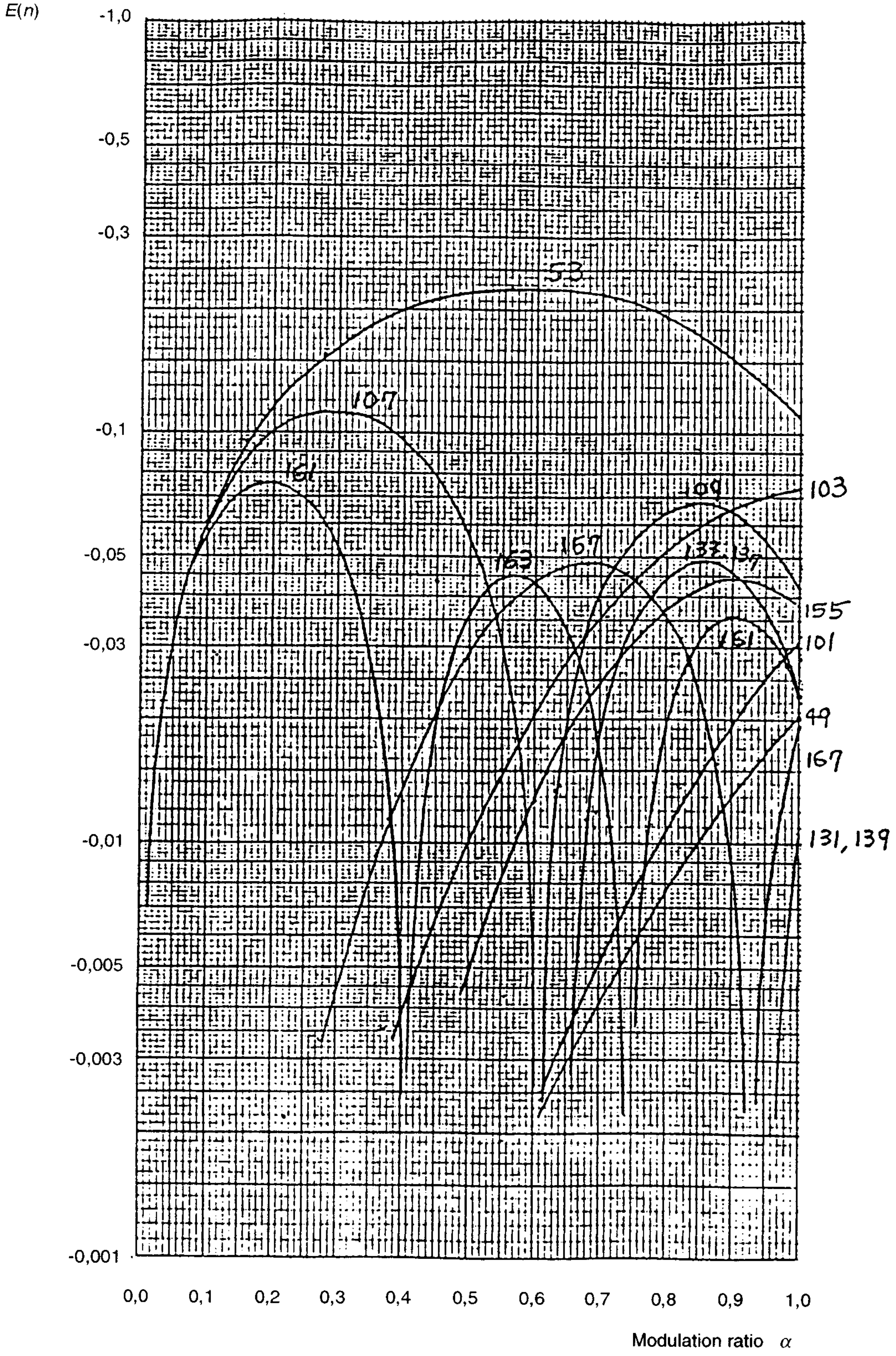


Figure A.12b

**Figure A.12** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 15

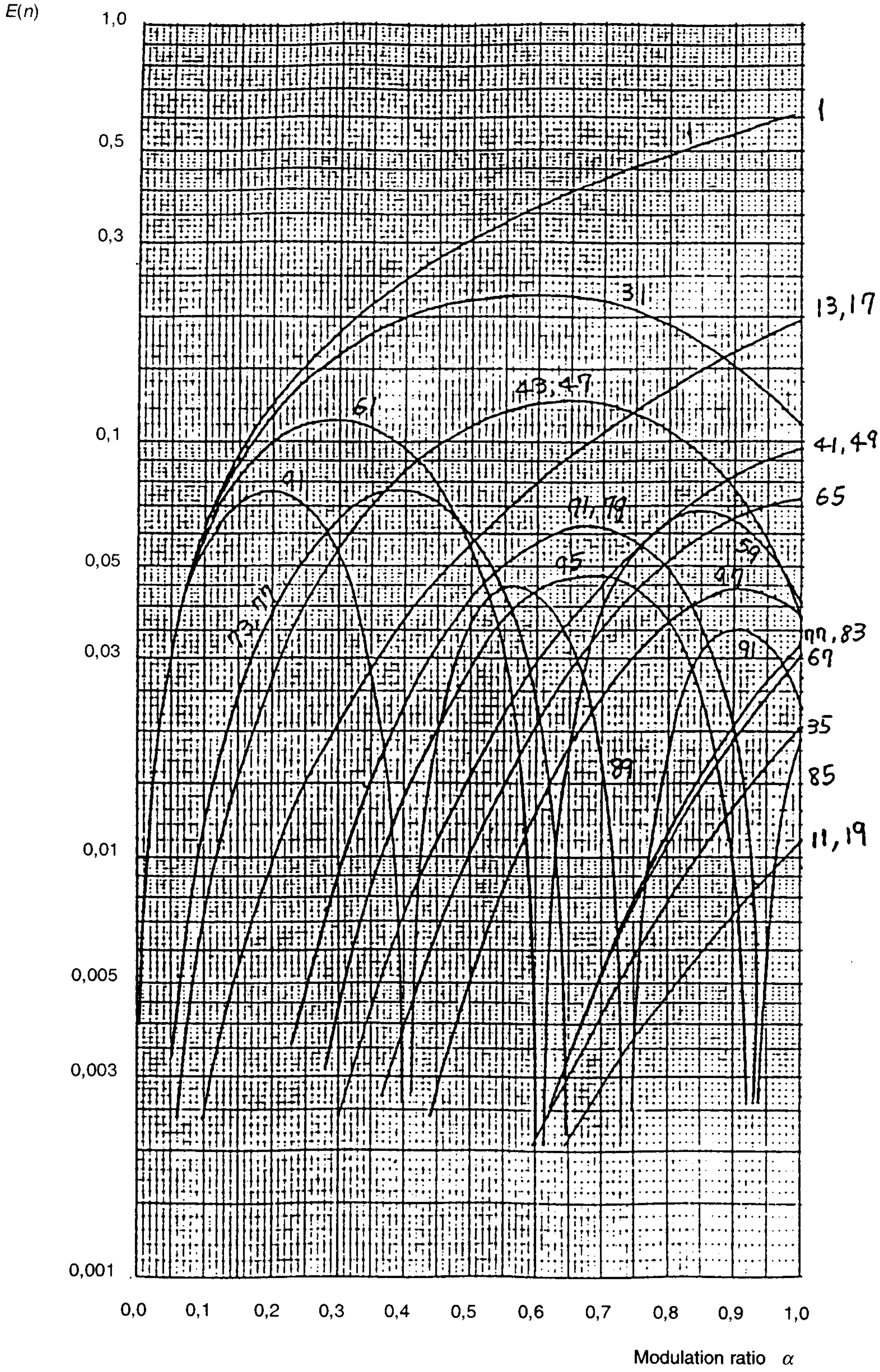


Figure A.12c

**Figure A.12** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 15

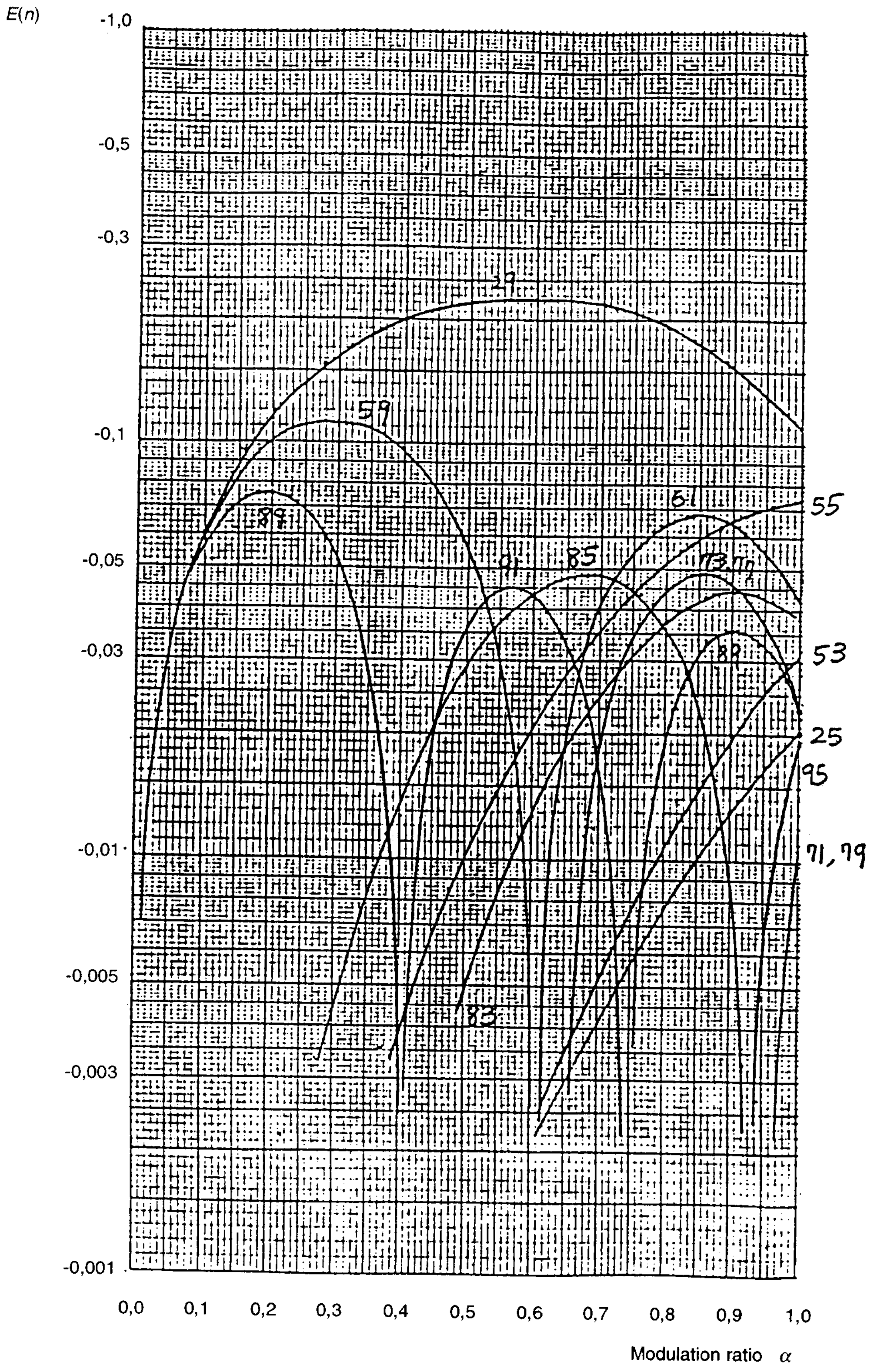


Figure A.12d

**Figure A.12** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 9

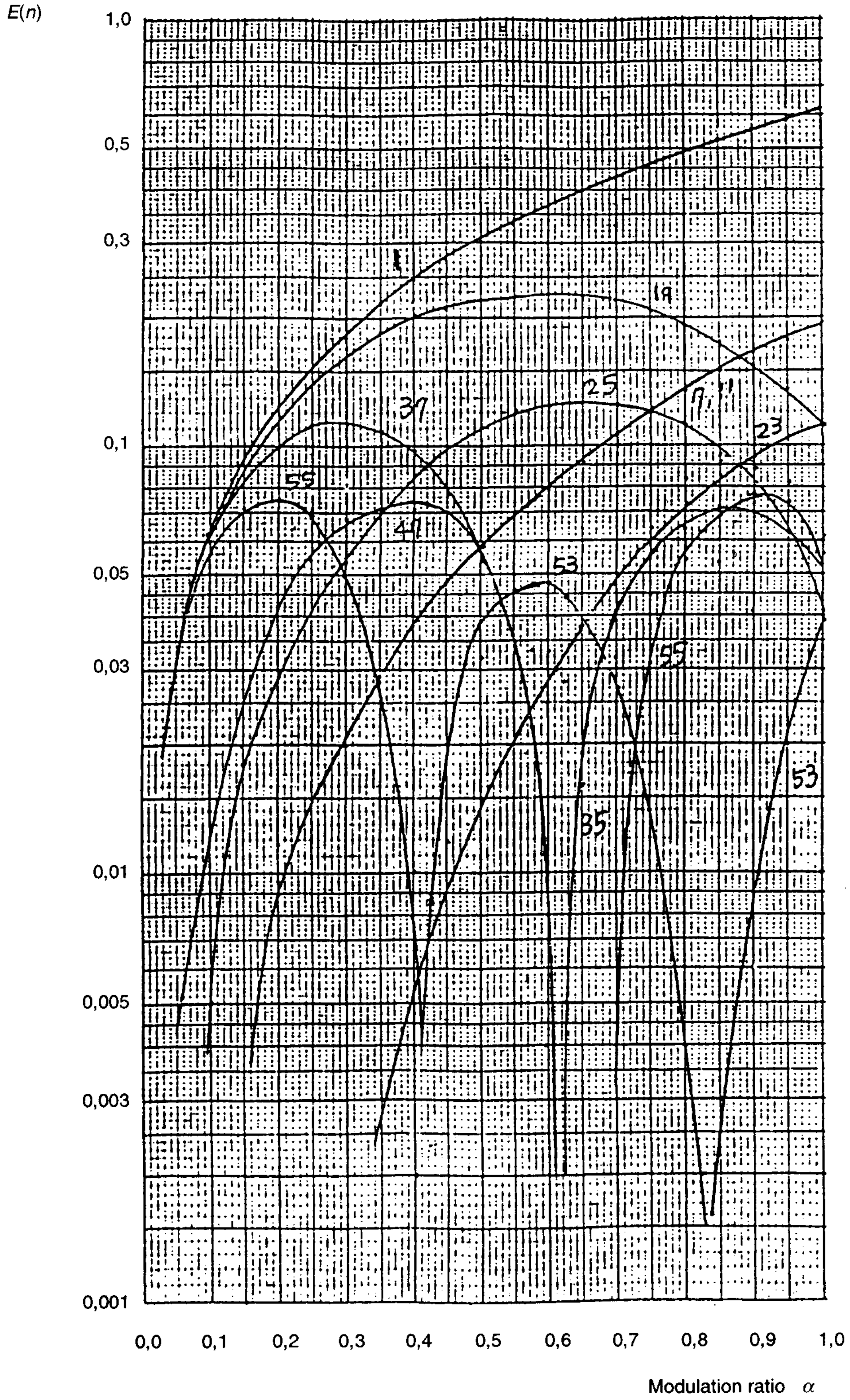


Figure A.12e

**Figure A.12** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 9

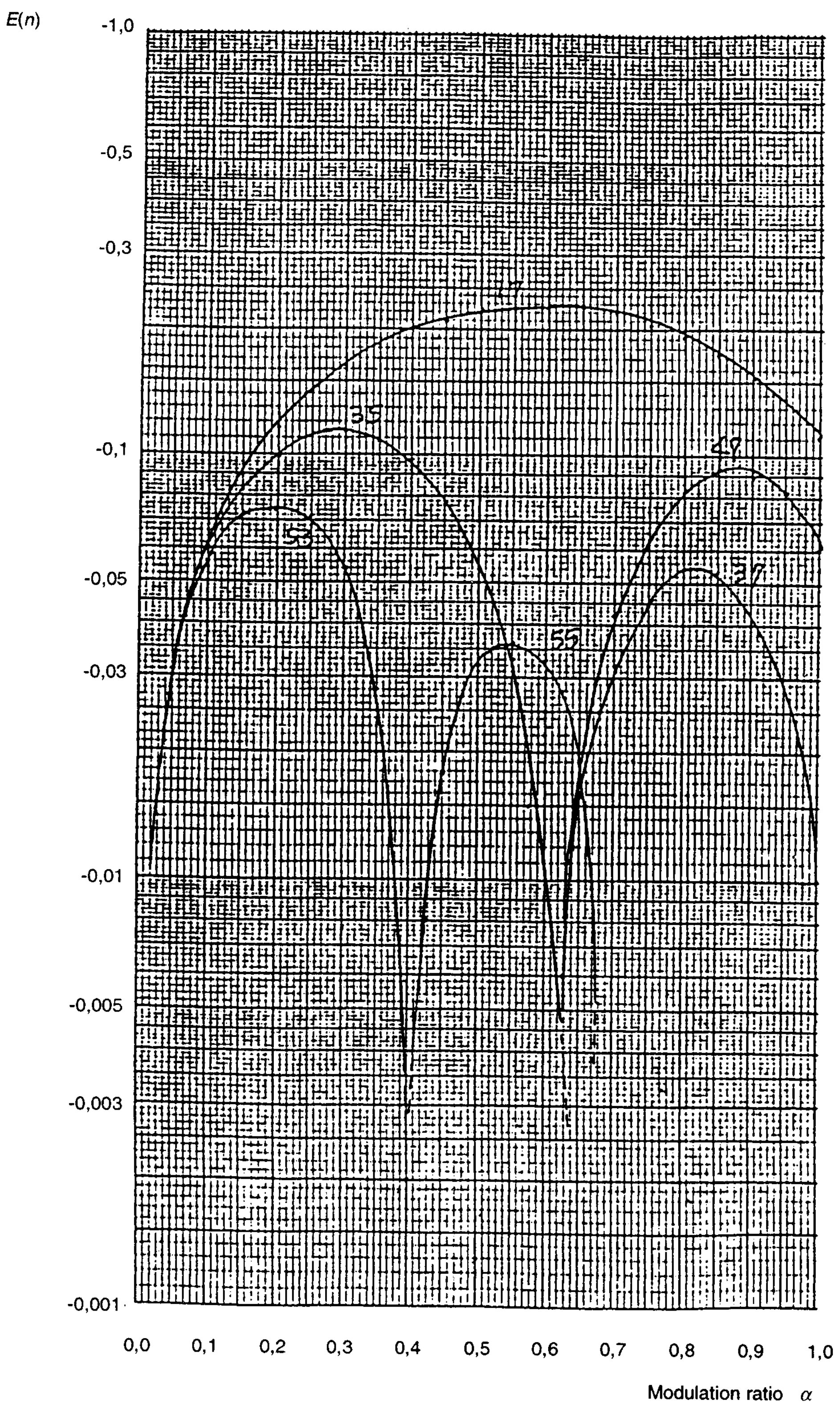


Figure A.12f

Figure A.12 *(continued)*

Modulation scheme:
rectangular-triangular modulation

Number of pulses: 3

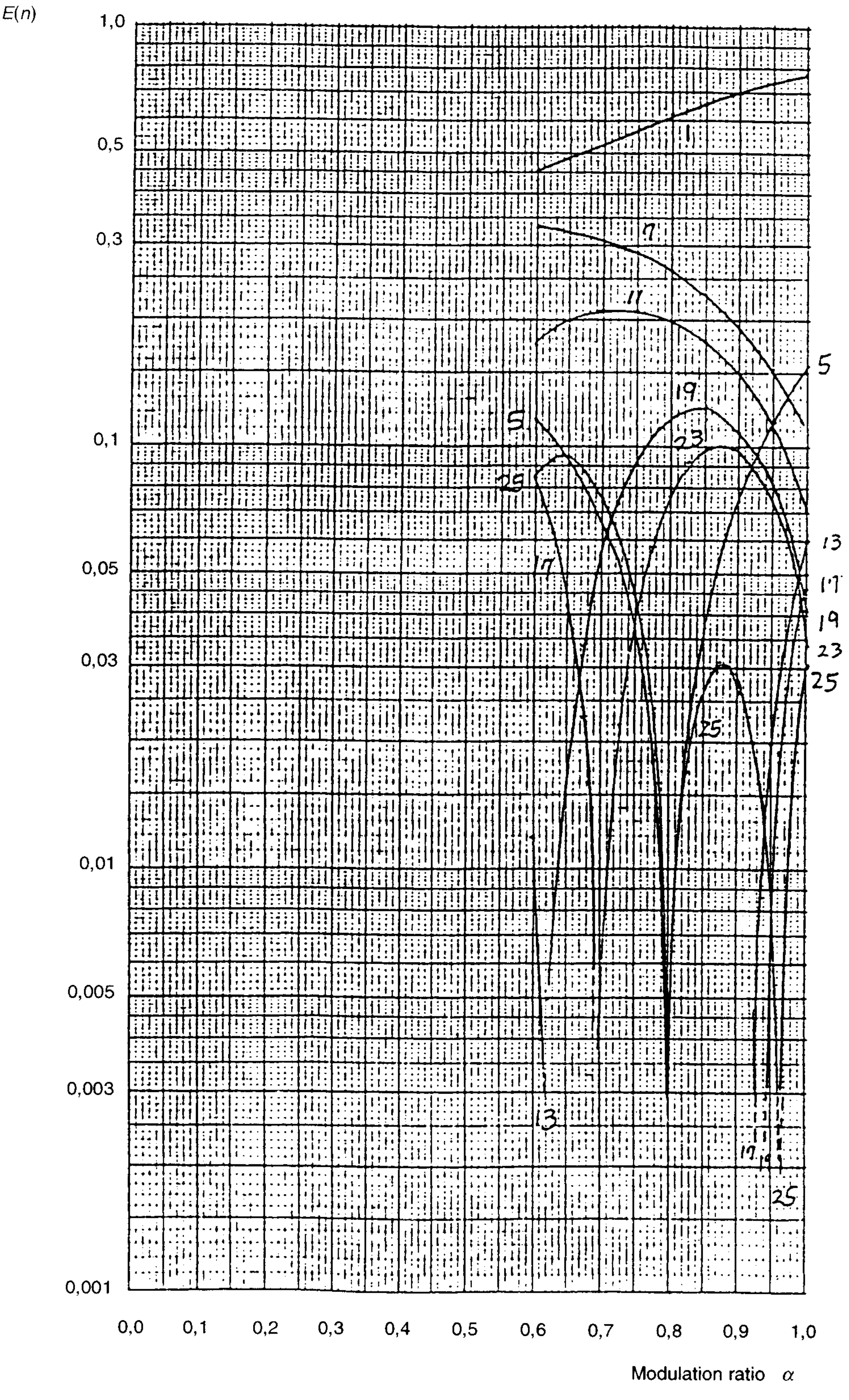


**Figure A.12g**

**Figure A.12** *(continued)*

Modulation scheme:
rectangular-triangular modulation

Number of pulses: 3

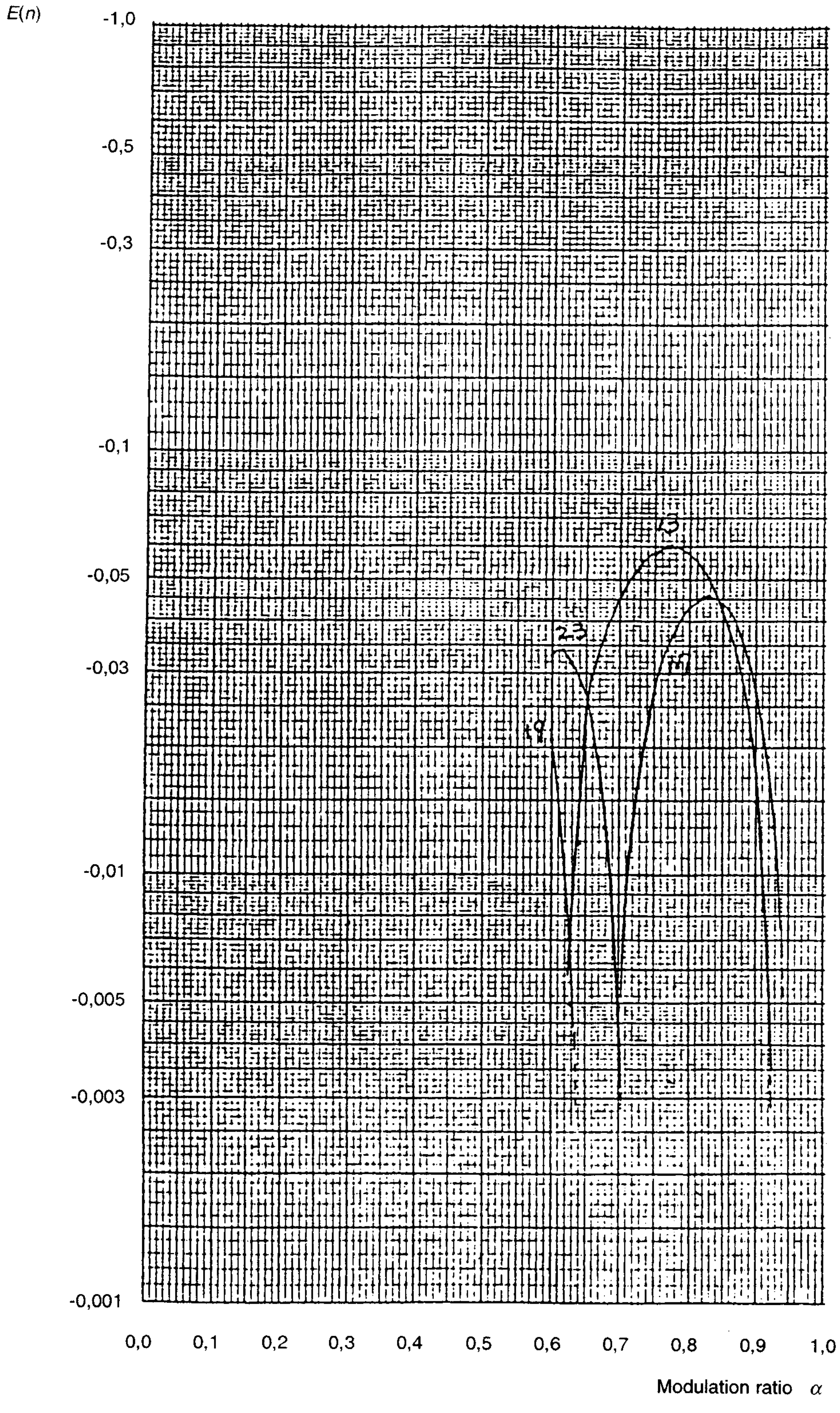


Figure A.12h

**Figure A.12** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 27
Displacement factor: 0,75

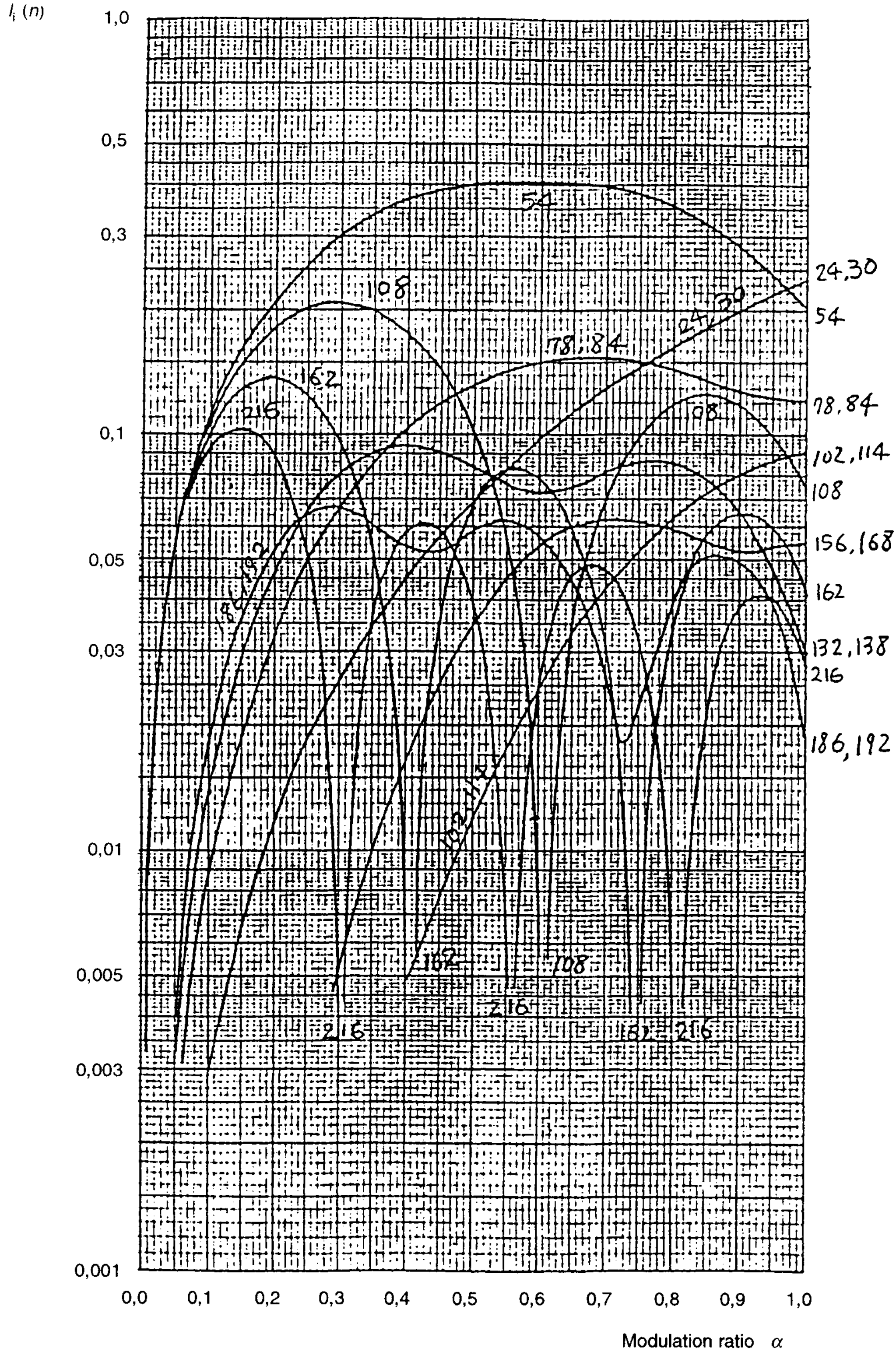


Figure A.13a

Figure Harmonic input current

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 27
Displacement factor: 0,8

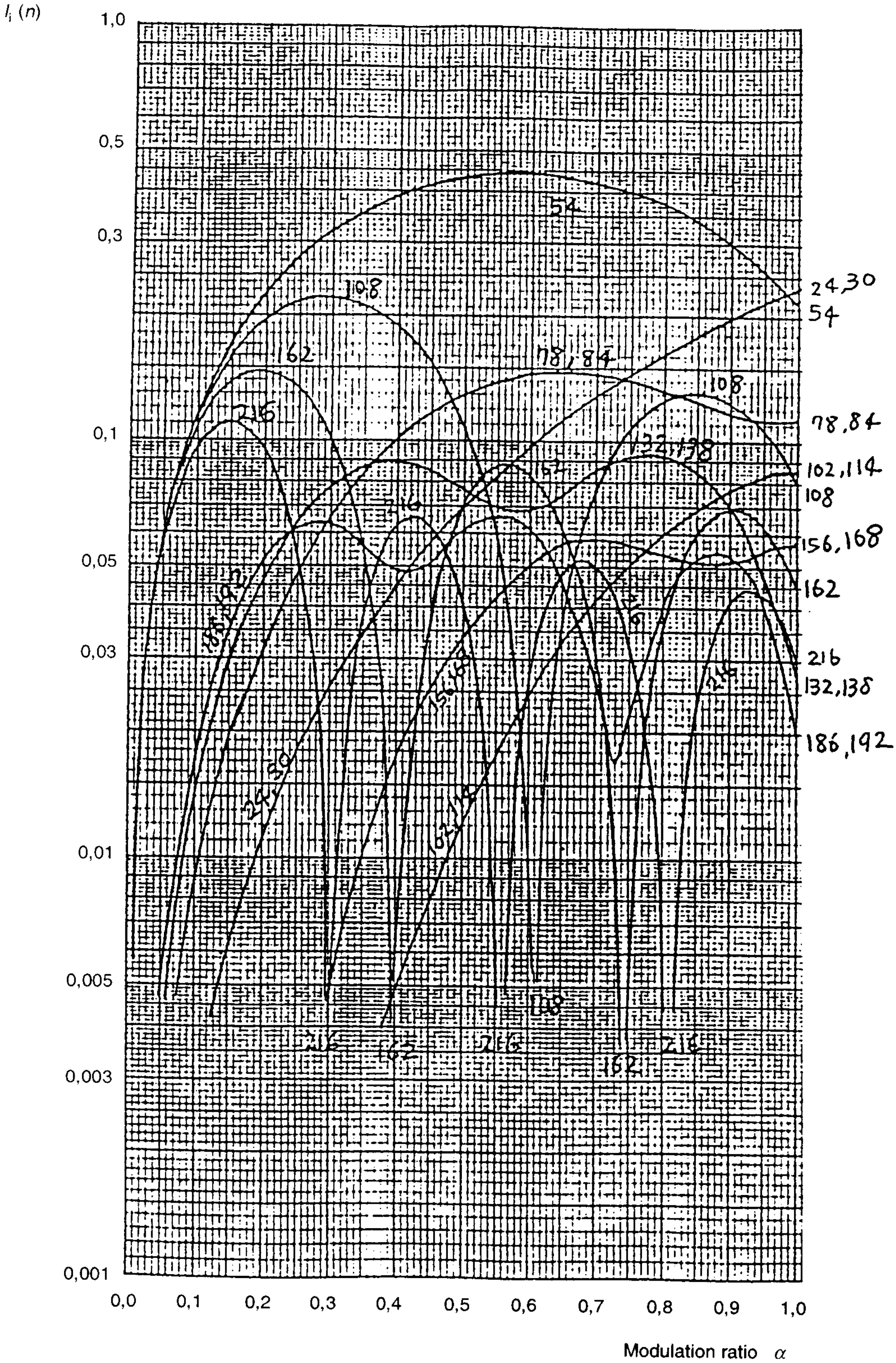


Figure A.13b

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 27
Displacement factor: 0,85

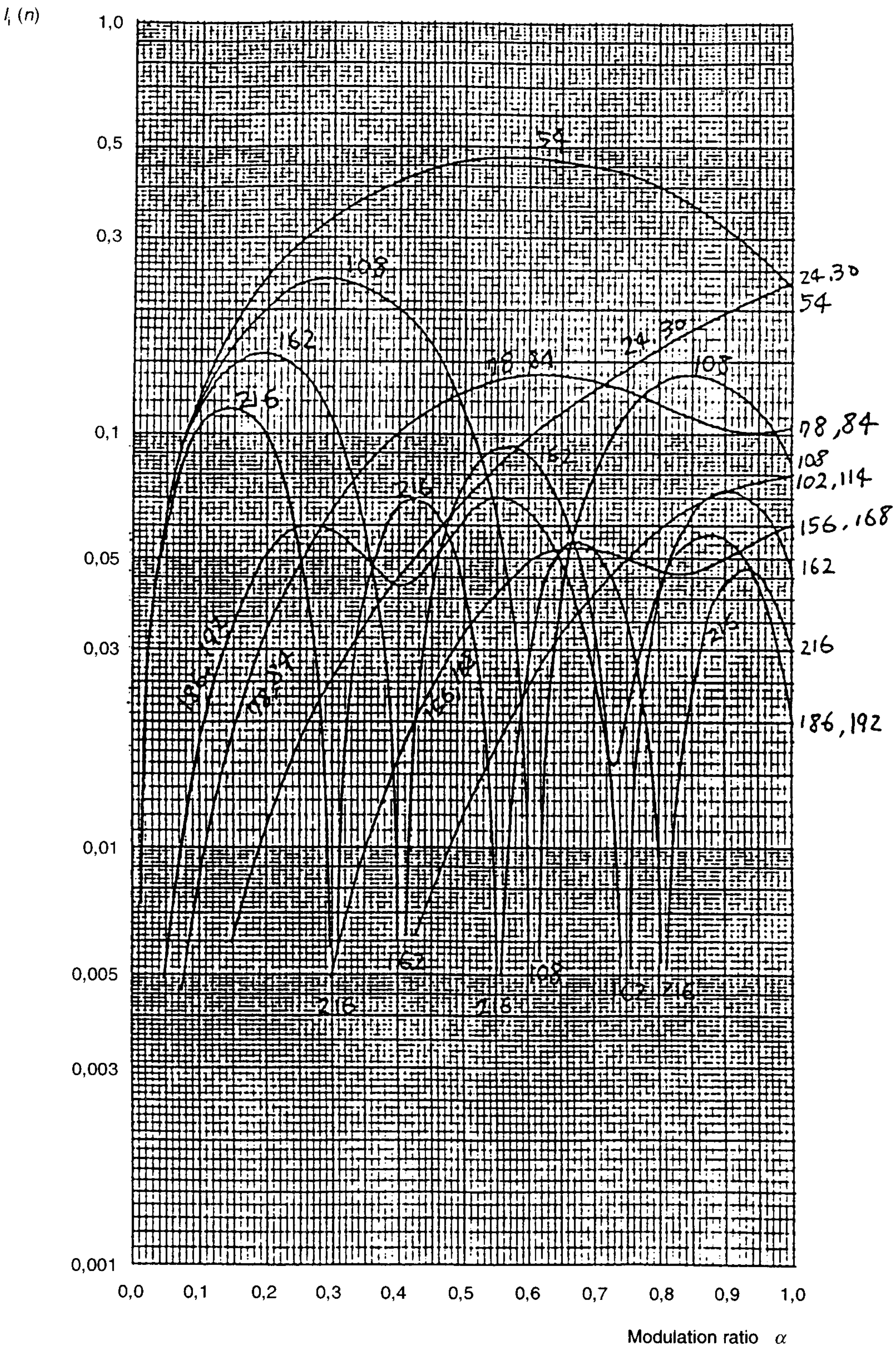


Figure A.13c

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 27
Displacement factor: 0,9

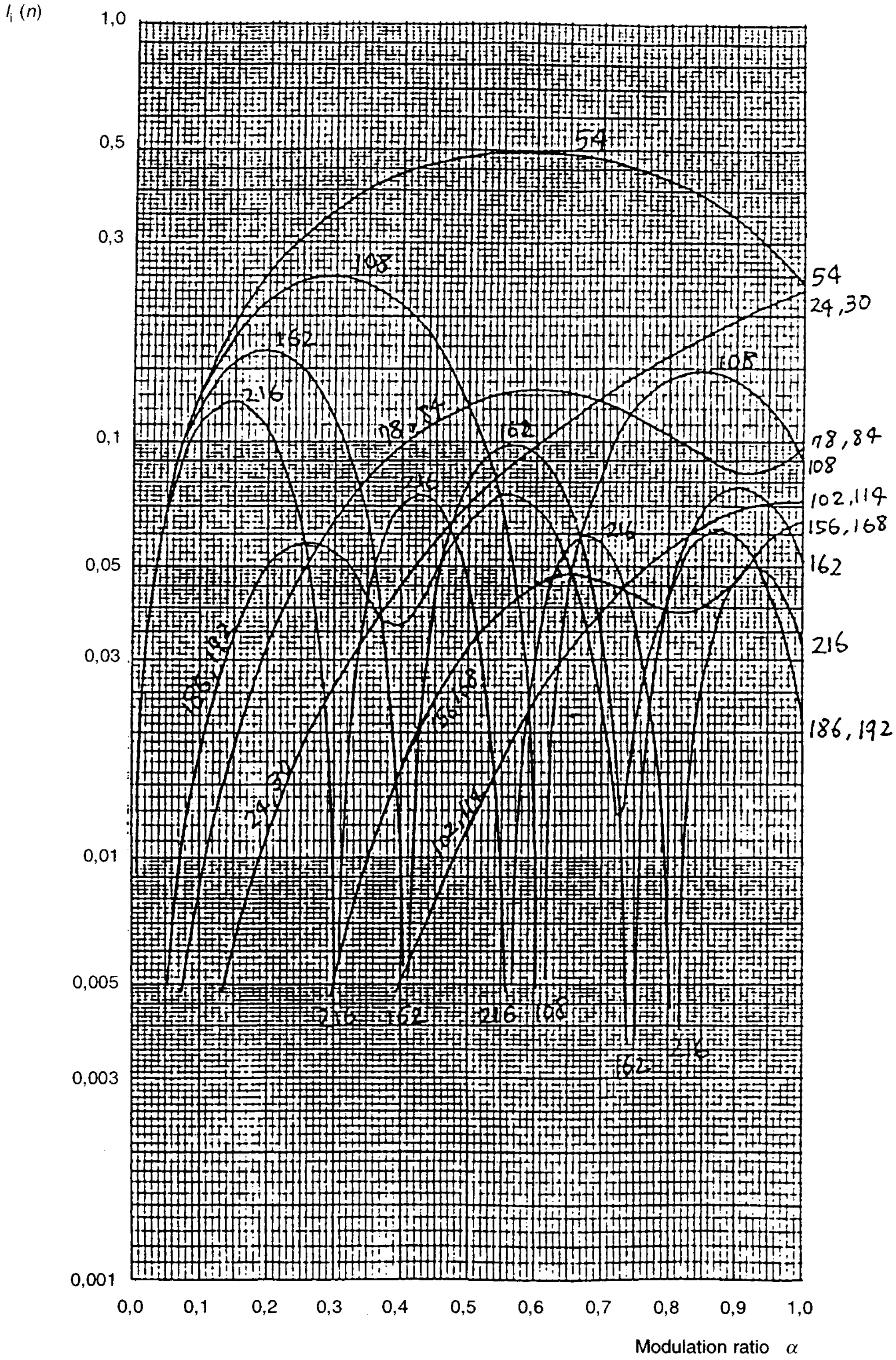


Figure A.13d

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 27
Displacement factor: 1,0

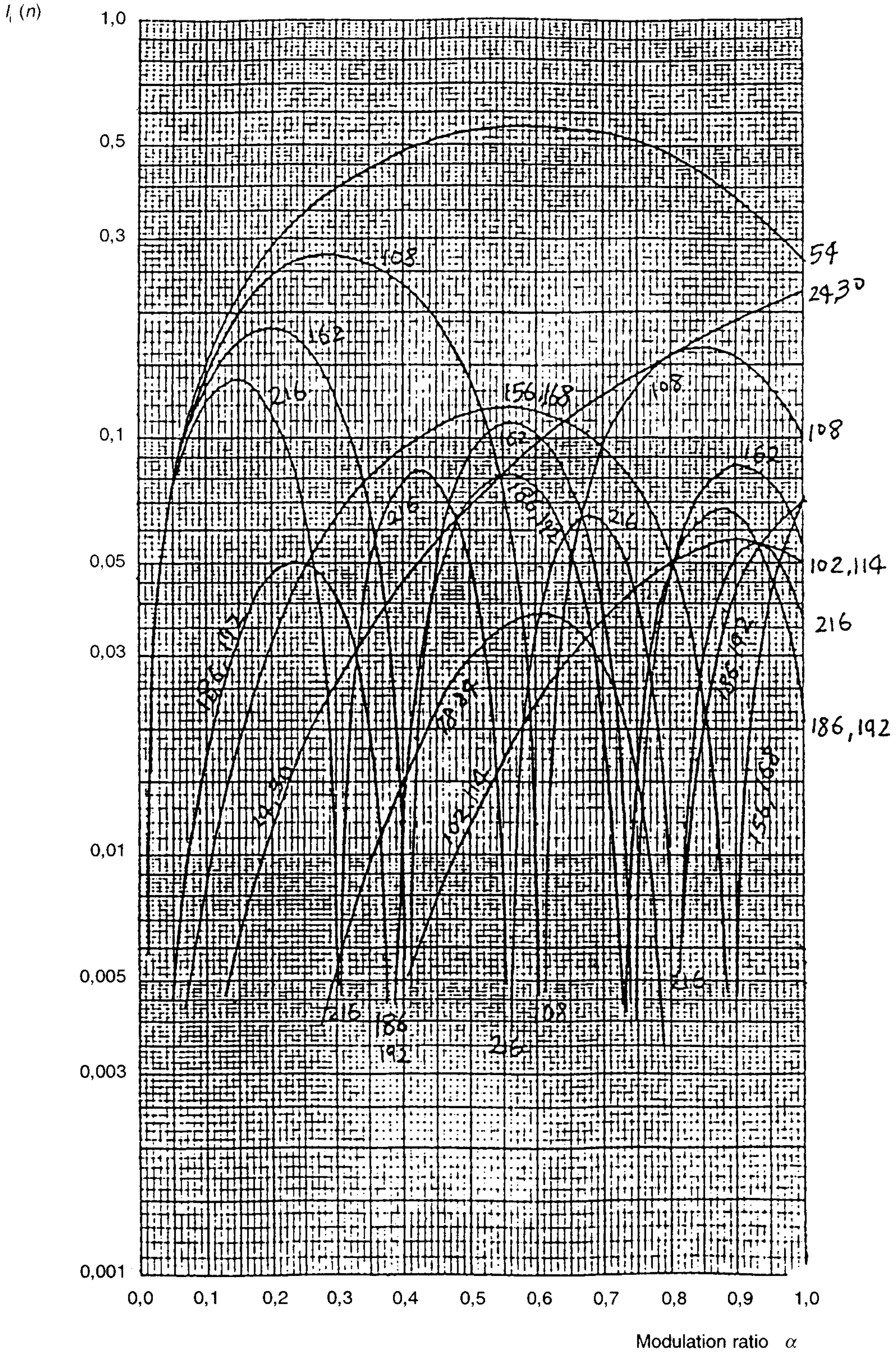


**Figure A.13e**

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 15
Displacement factor: 0,75

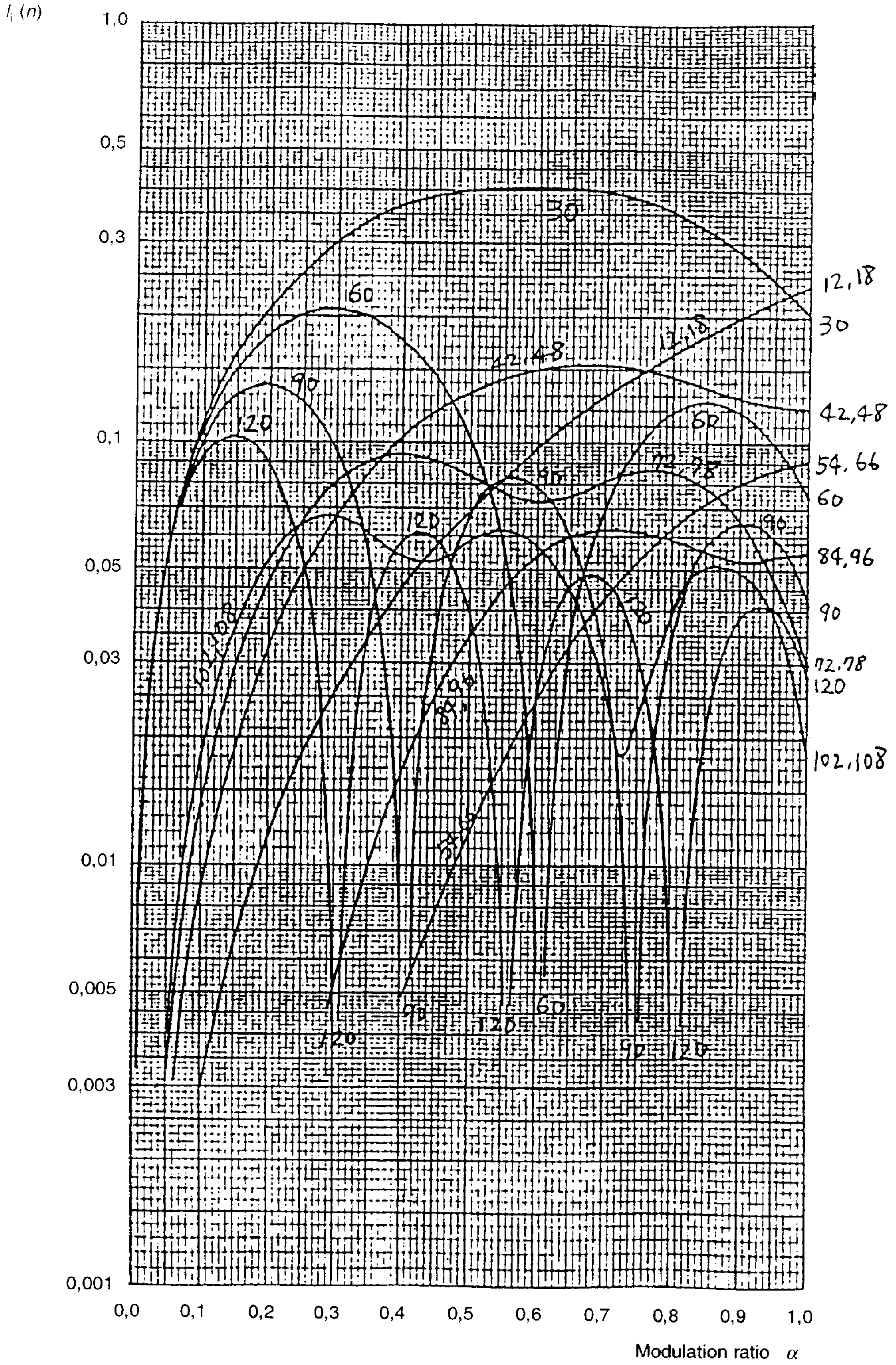


Figure A.13f

Figure A.13 *(continued)*

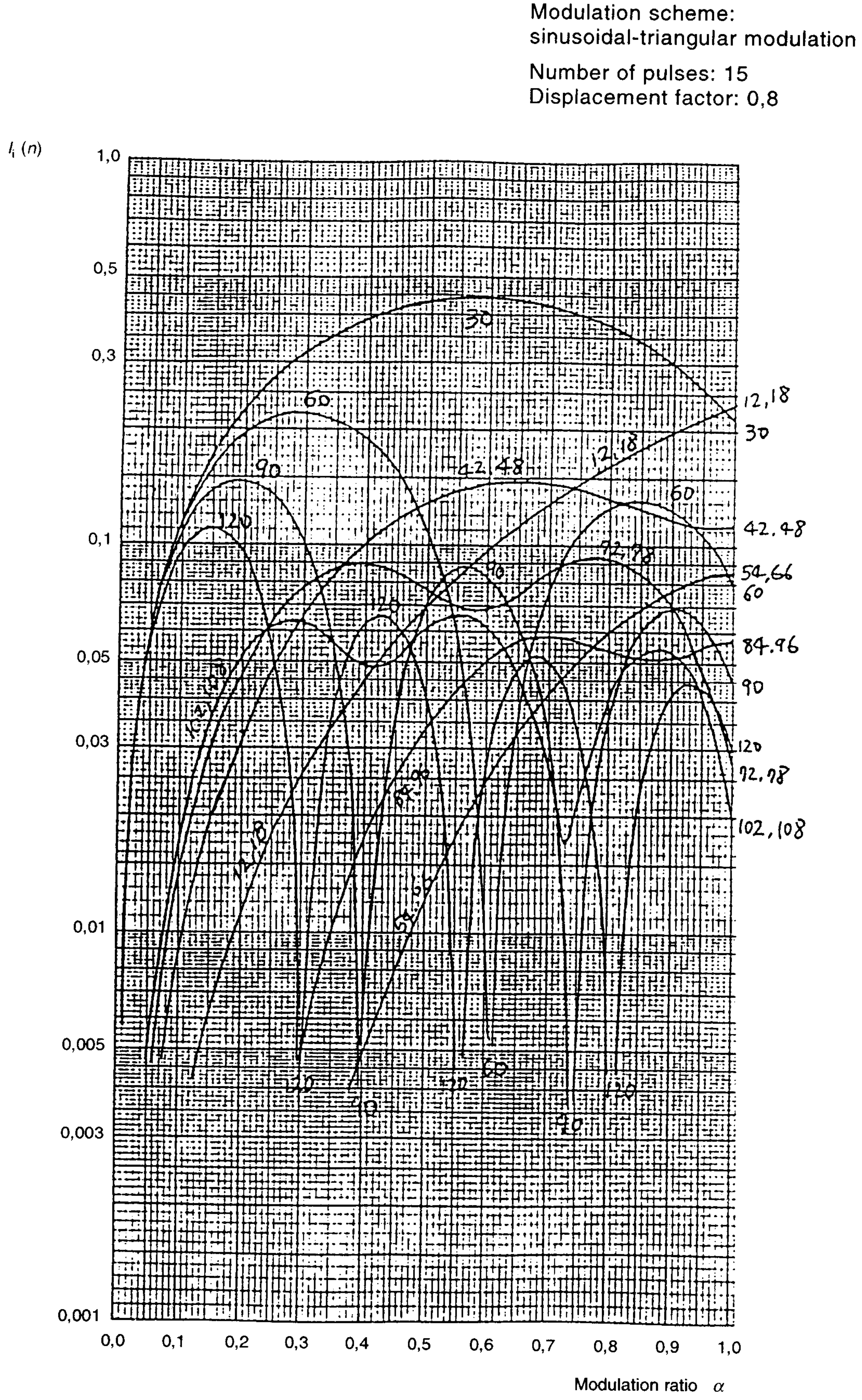


**Figure A.13g**

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 15
Displacement factor: 0,85

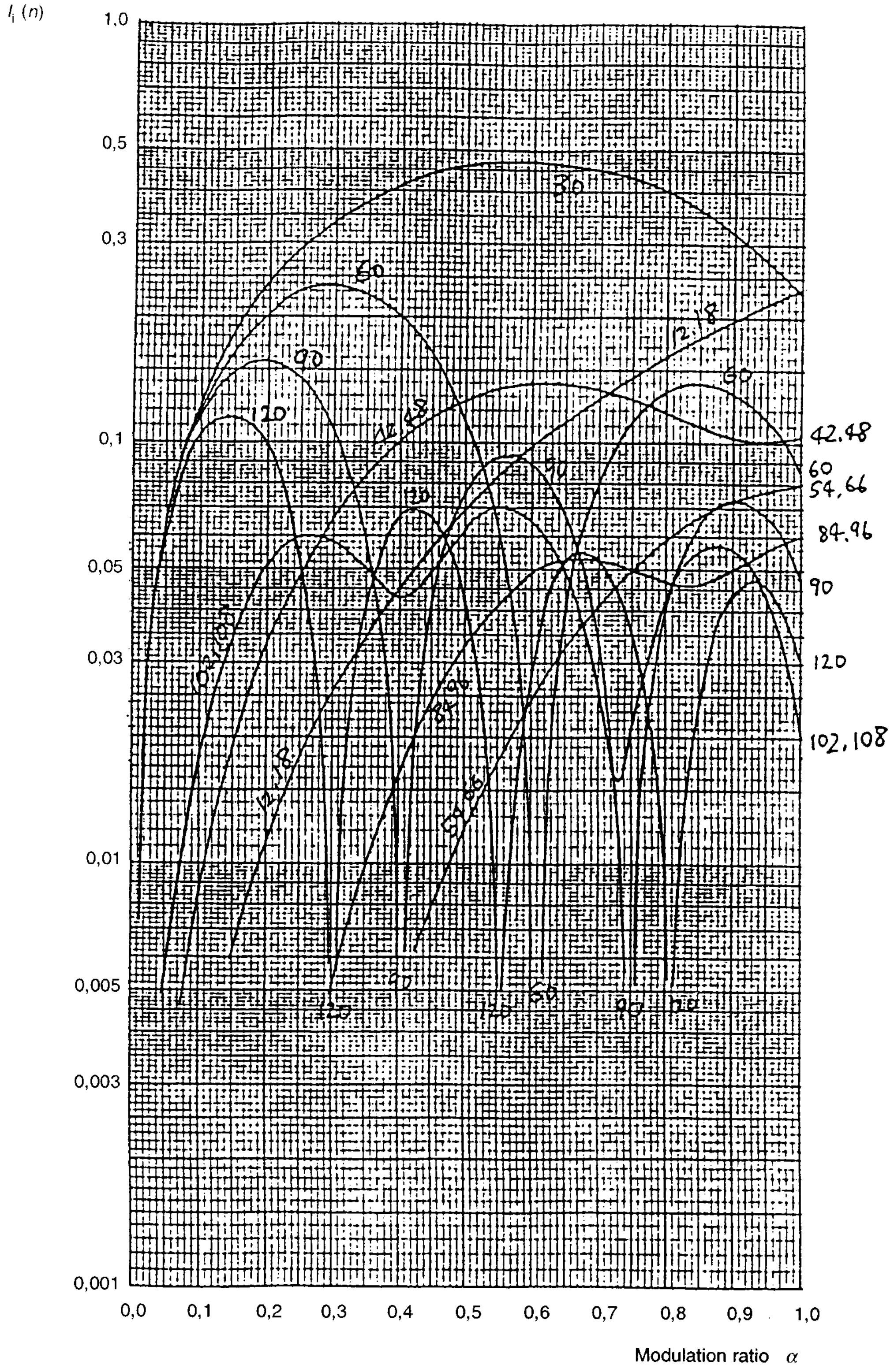


Figure A.13h

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 15
Displacement factor: 0,9

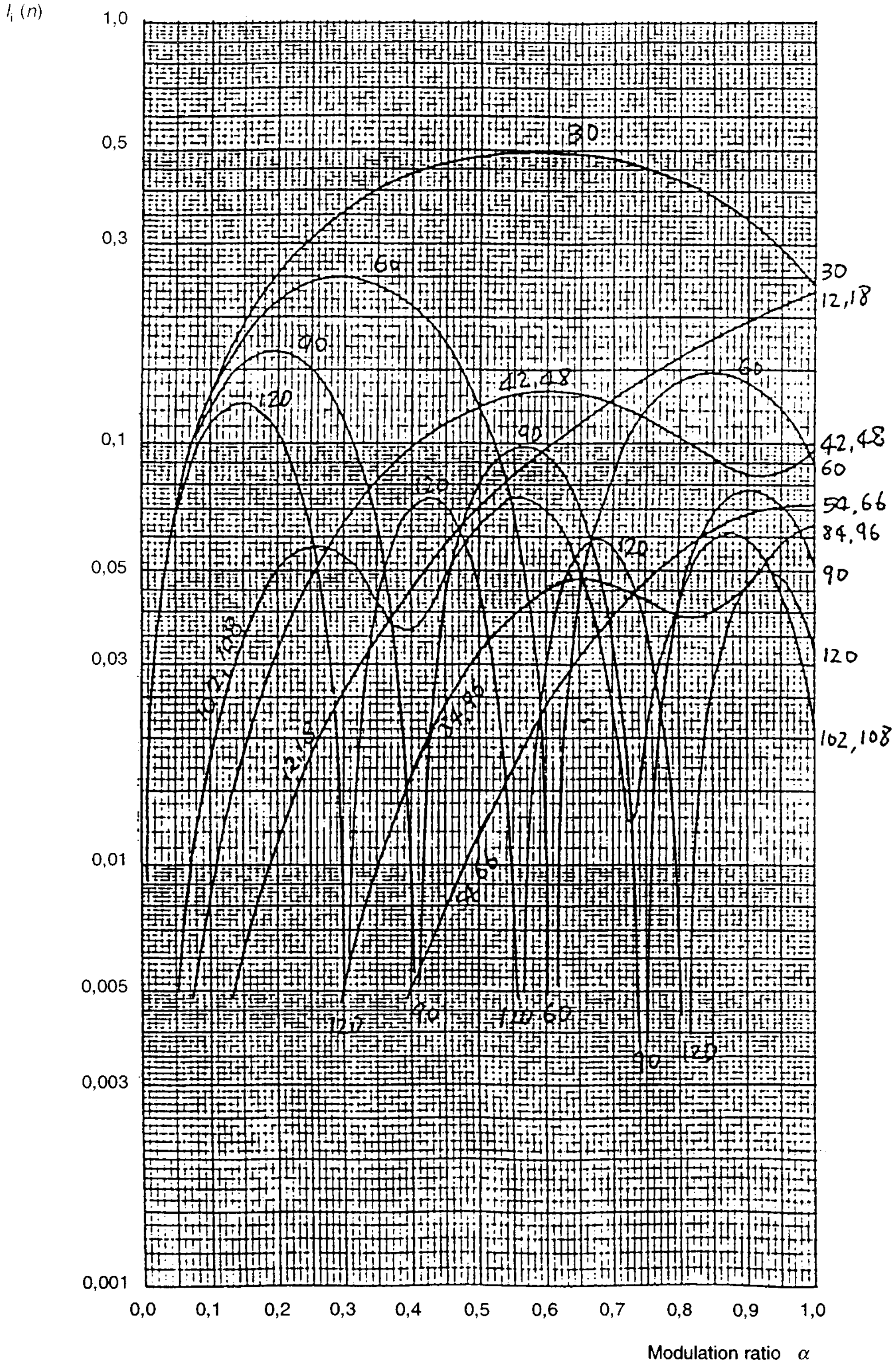


Figure A.13i

Figure A.13 *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 15
Displacement factor: 1,0

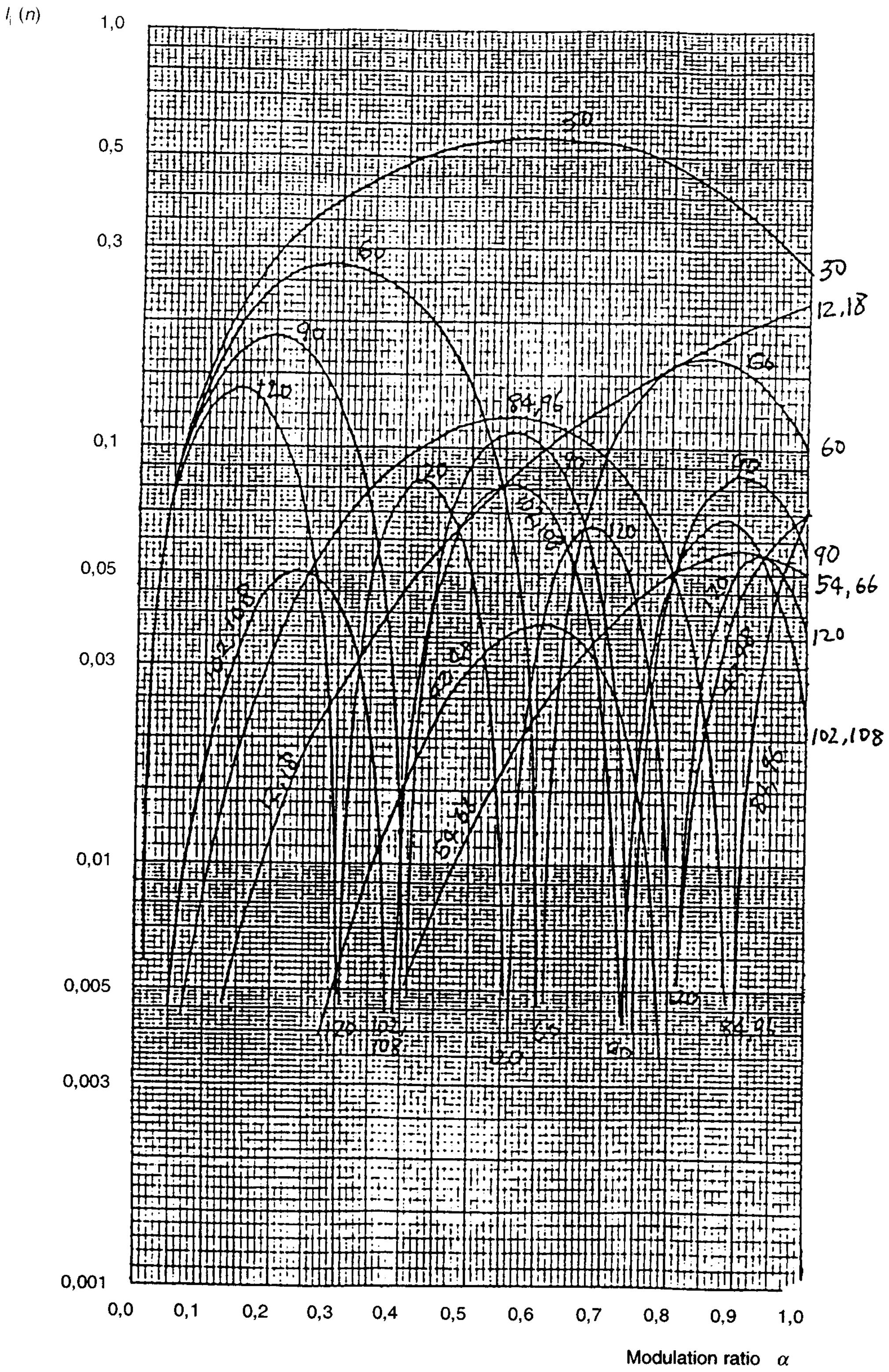


Figure A.13j

Figure A.13 *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 9
Displacement factor: 0,75

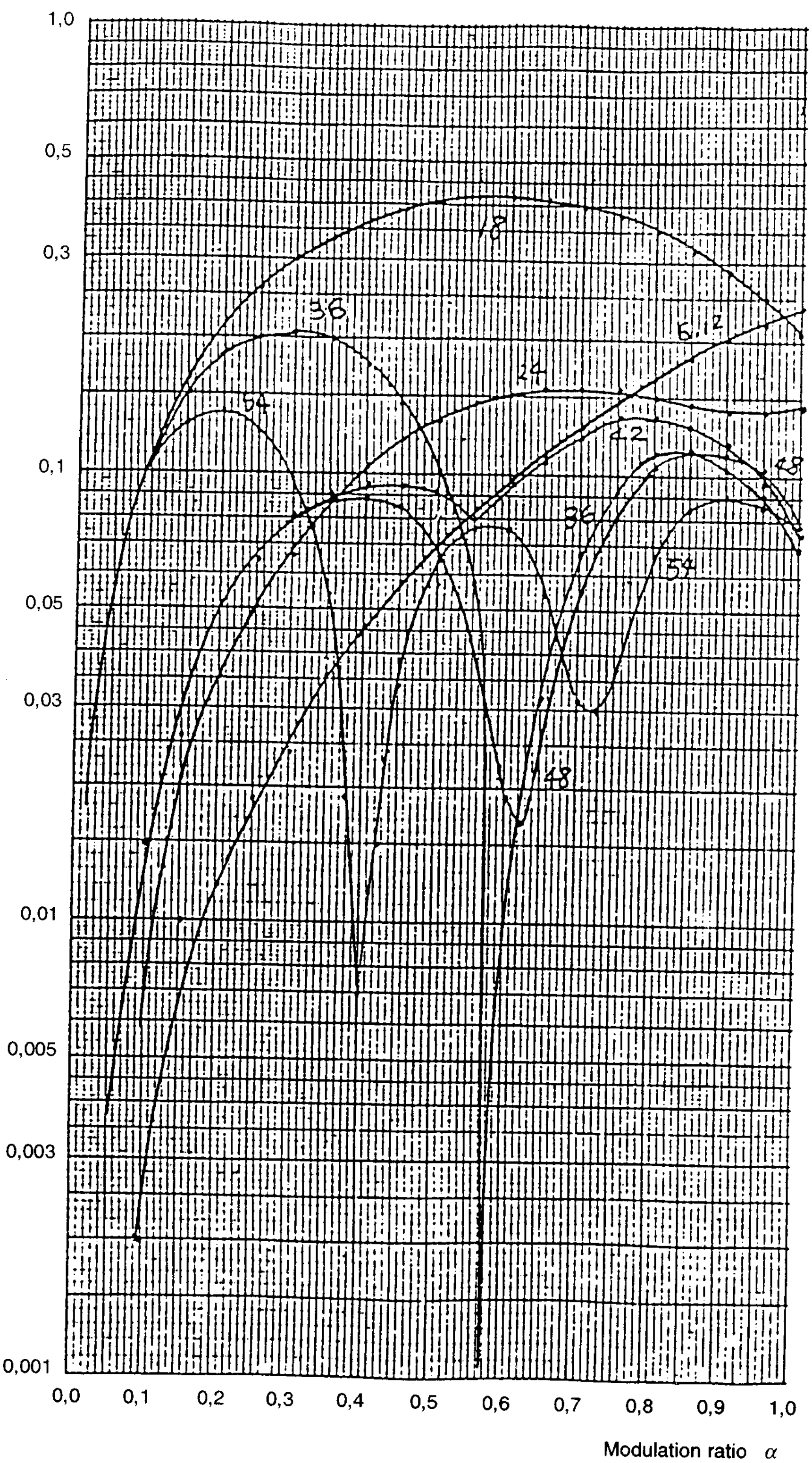


Figure A.13k

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 9
Displacement factor: 0,8

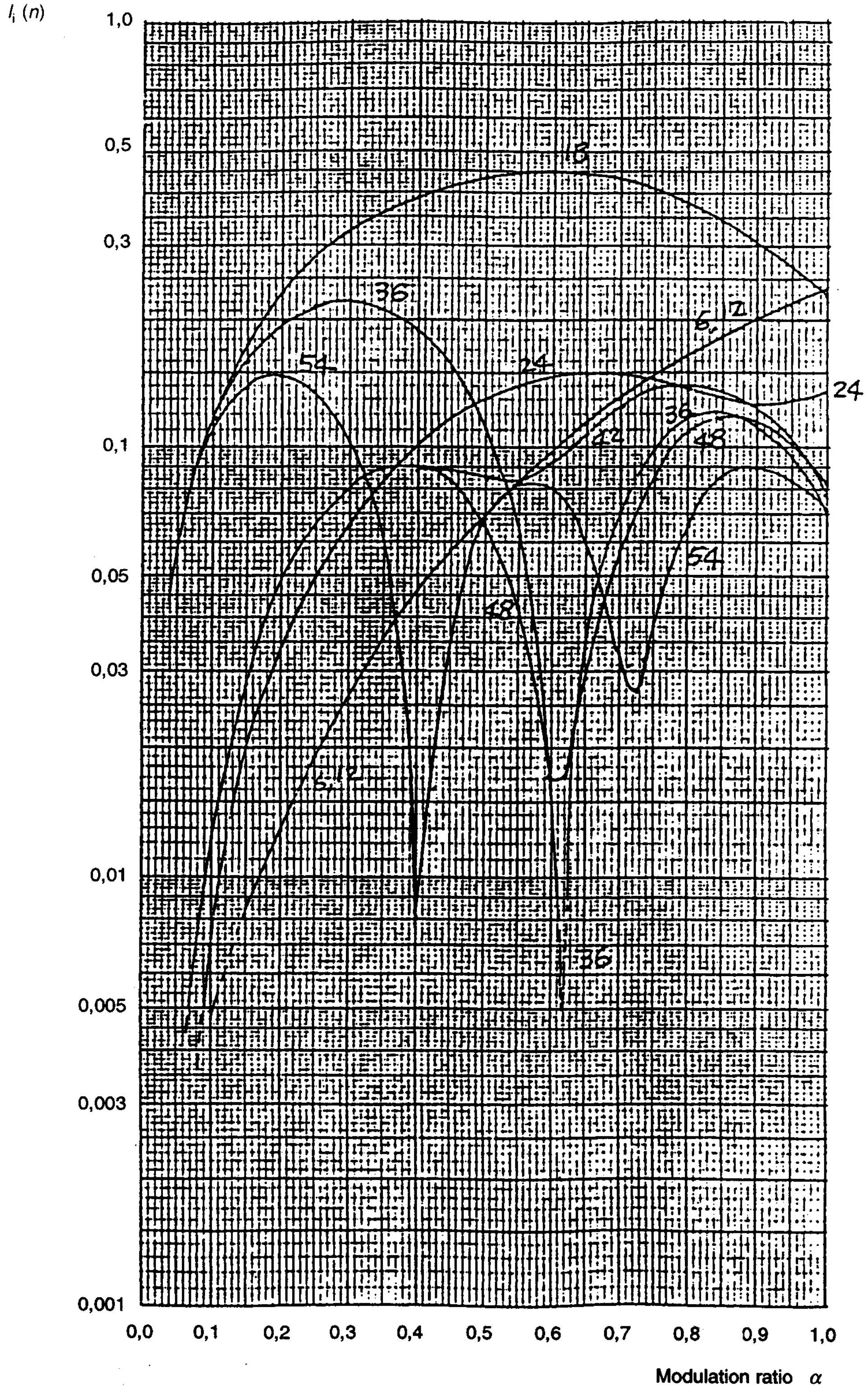


Figure A.13l

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 9
Displacement factor: 0,85

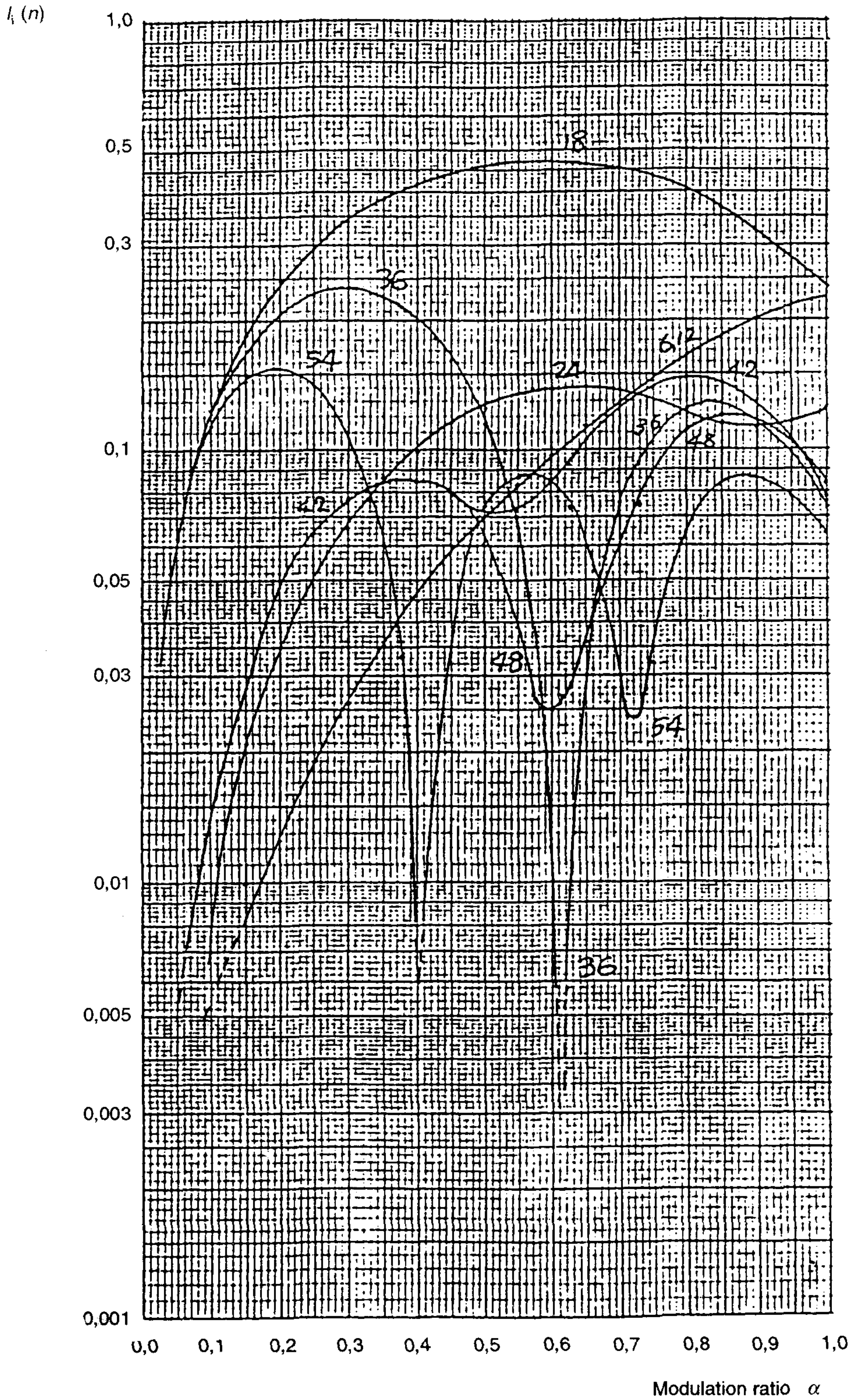


Figure A.13m

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 9
Displacement factor: 0,9

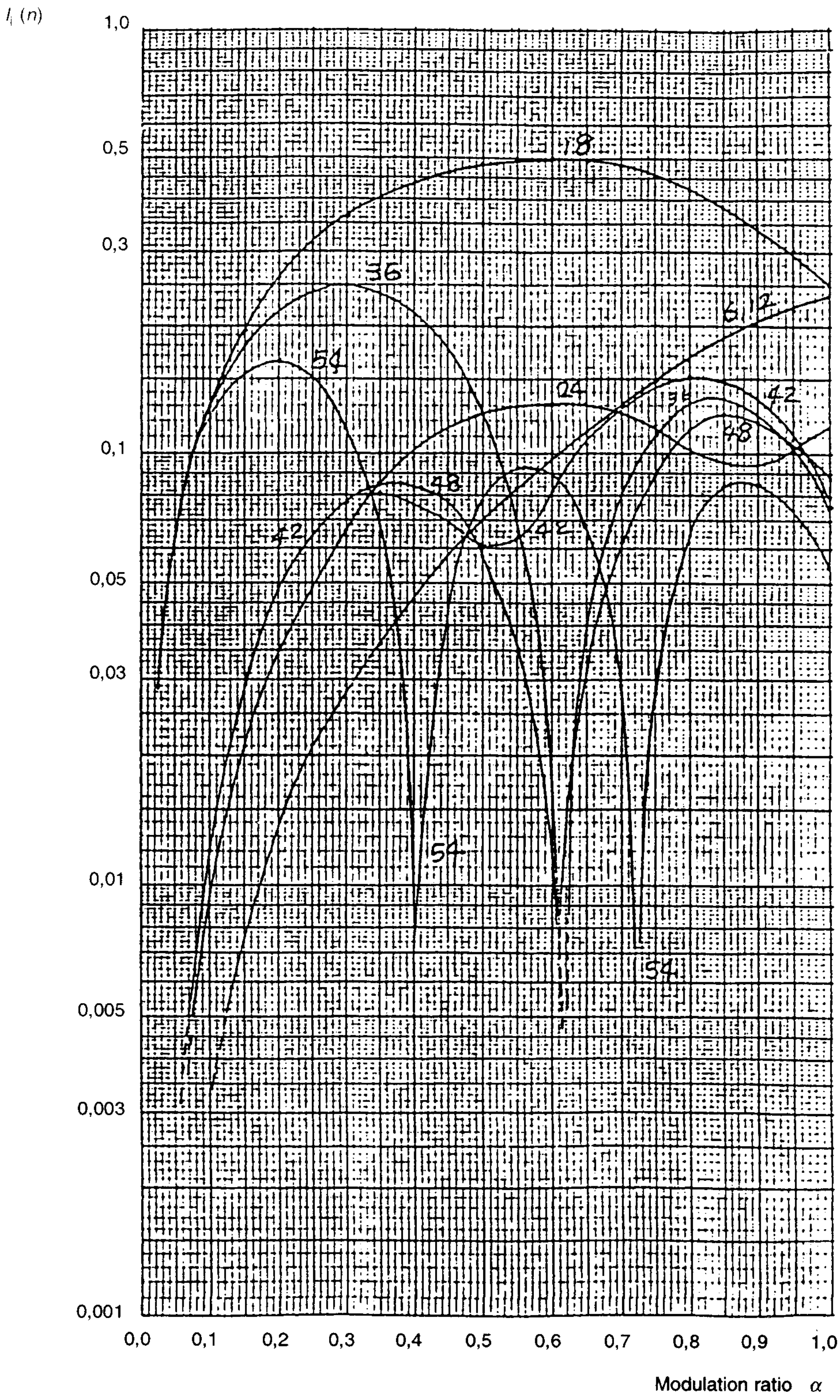


Figure A.13n

**Figure A.13** *(continued)*

Modulation scheme:
sinusoidal-triangular modulation

Number of pulses: 9
Displacement factor: 1,0

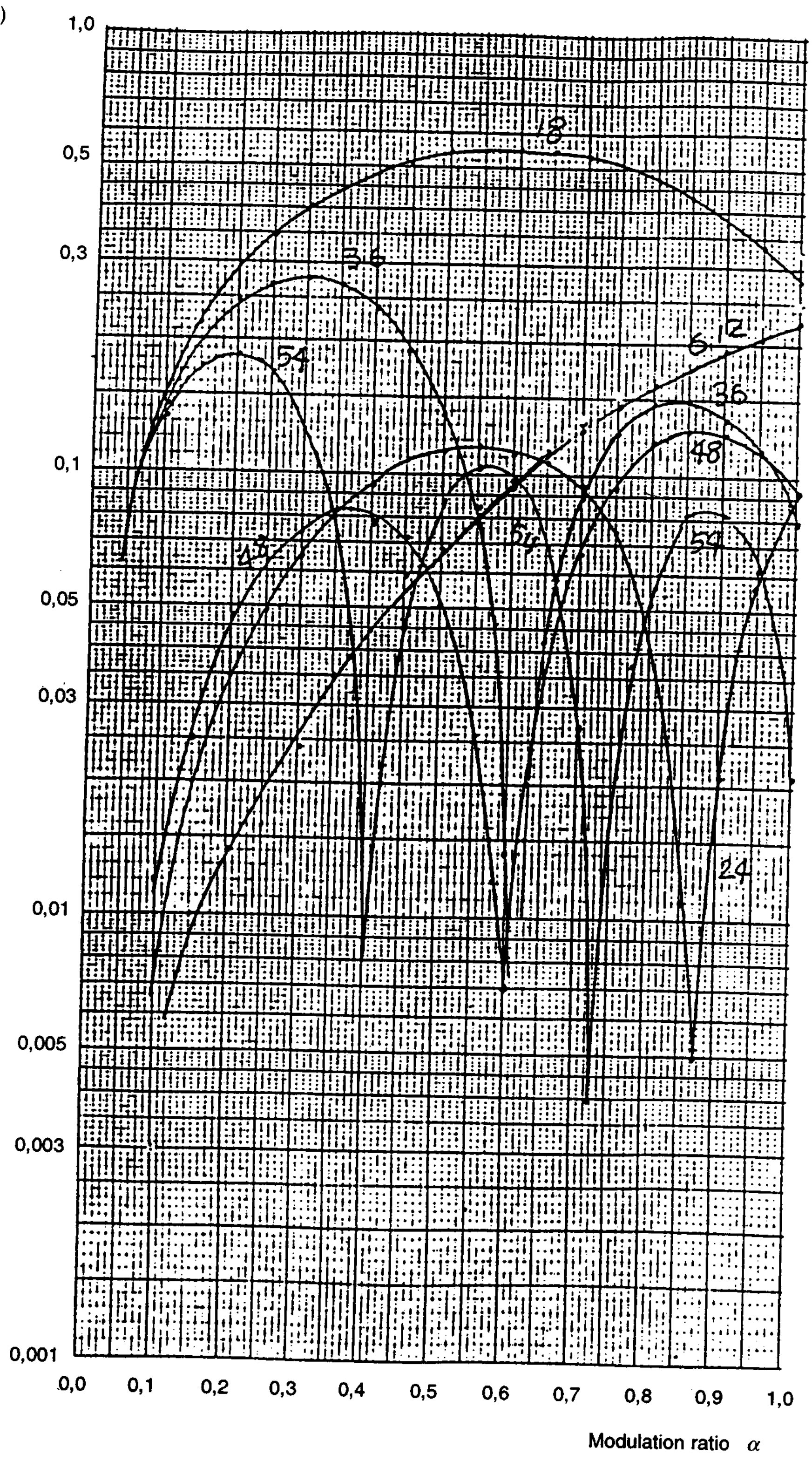


Figure A.13o

Figure A.13 *(continued)*

Modulation sc
rectangular-tr modulation

Number of pu
Displacement 0,75

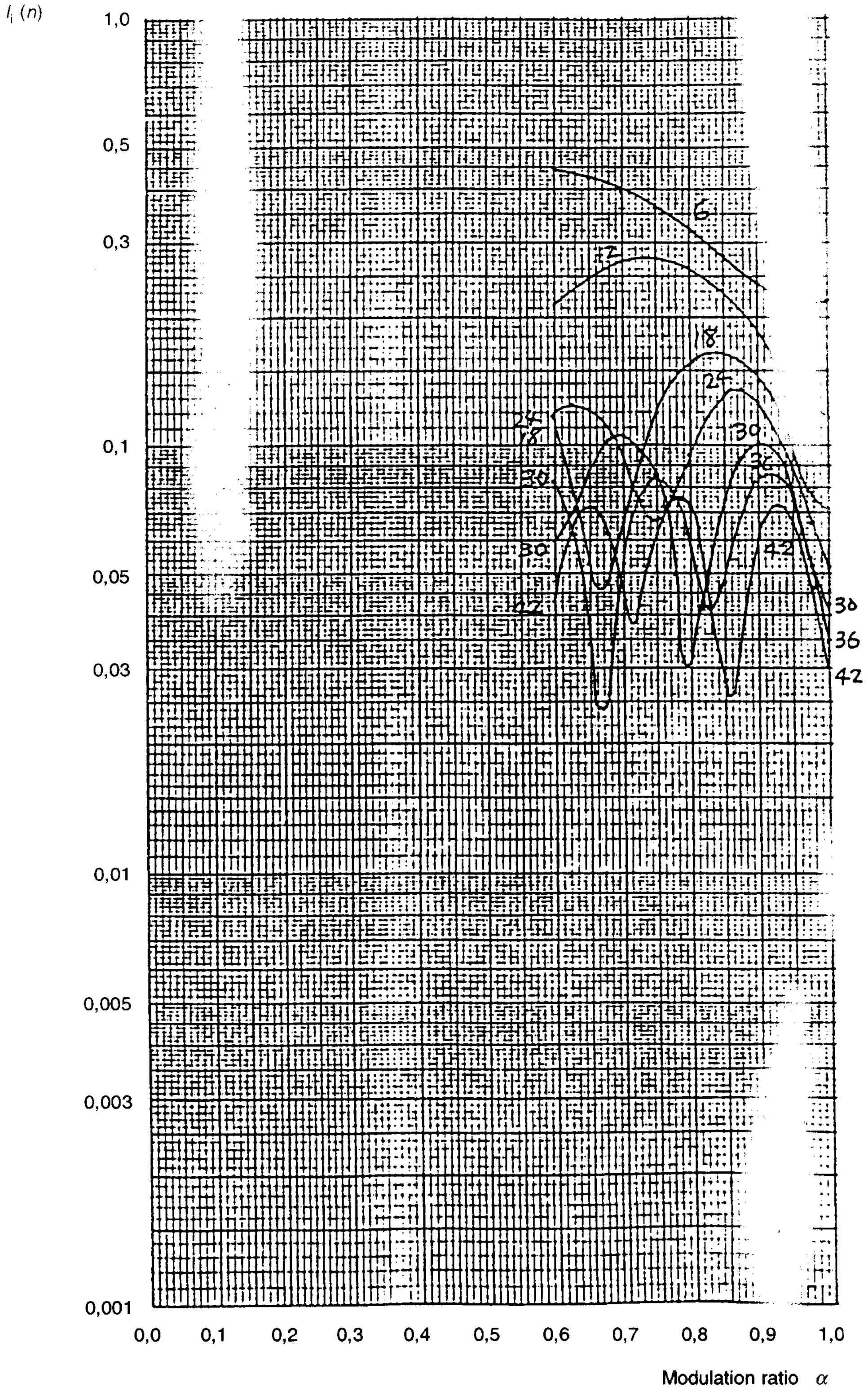


**Figure A.13p**

**Figure A.13** *(continued)*

Modulation scheme:
rectangular-triangular modulation

Number of pulses: 3
Displacement factor: 0,8

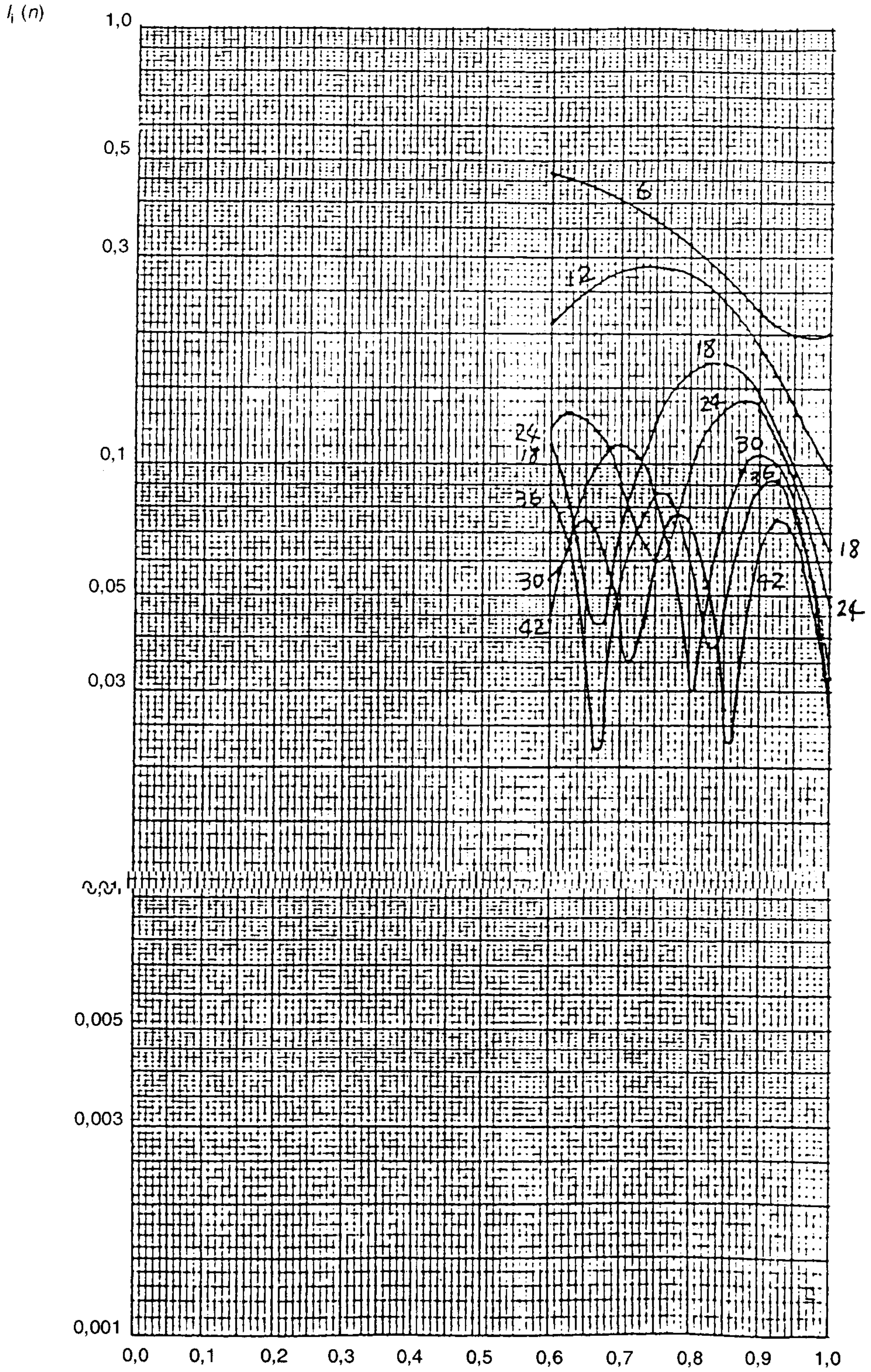


Figure A.13q

**Figure A.13** *(continued)*

Modulation scheme:
rectangular-triangular modulation

Number of pulses: 3
Displacement factor: 0,85

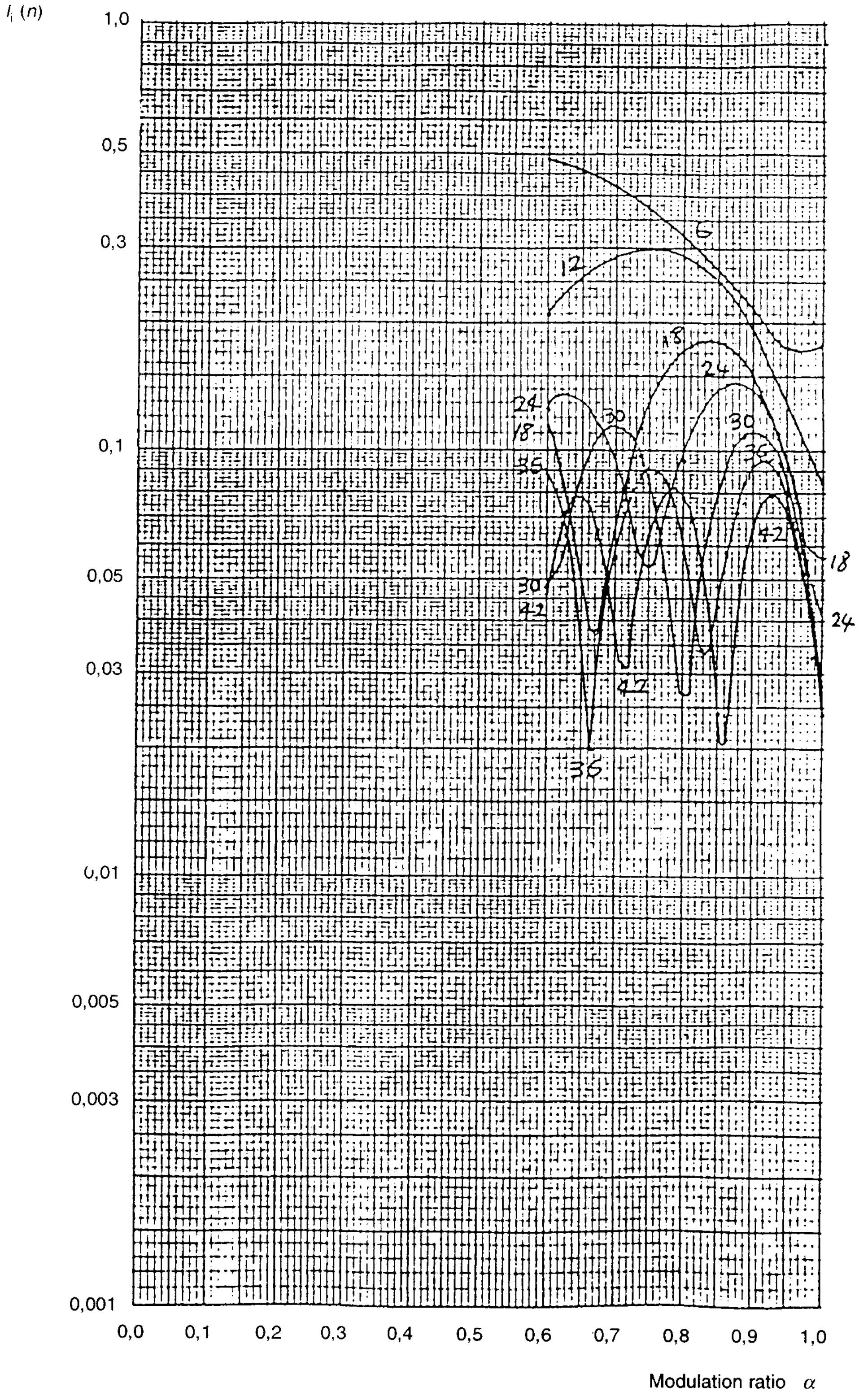


Figure A.13r

**Figure A.13** *(continued)*

Modulation scheme:
rectangular-triangular modulation

Number of pulses: 3
Displacement factor: 0,9

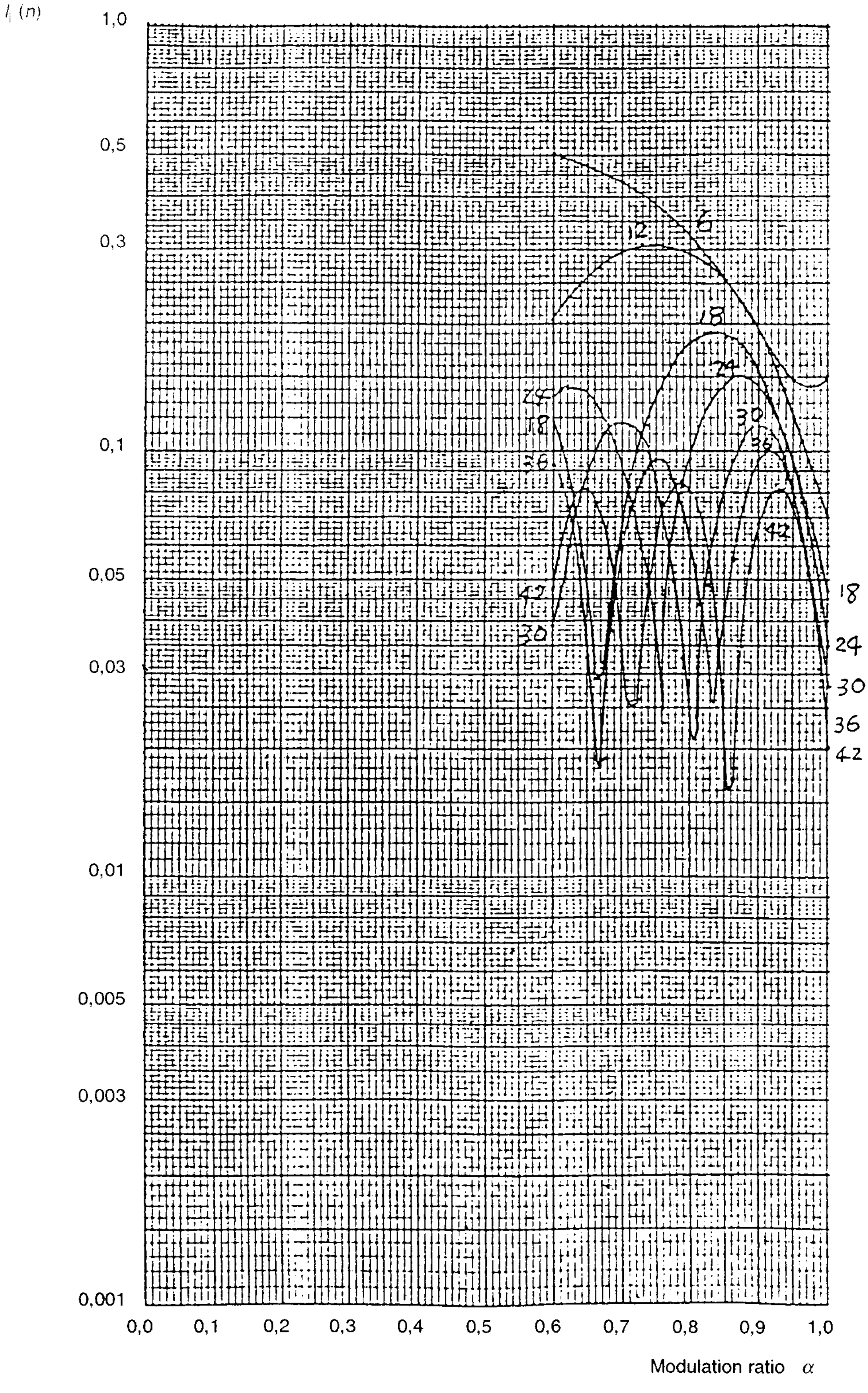


Figure A.13s

**Figure A.13** *(continued)*

Modulation scheme:
rectangular-triangular modulation

Number of pulses: 3
Displacement factor: 1,0

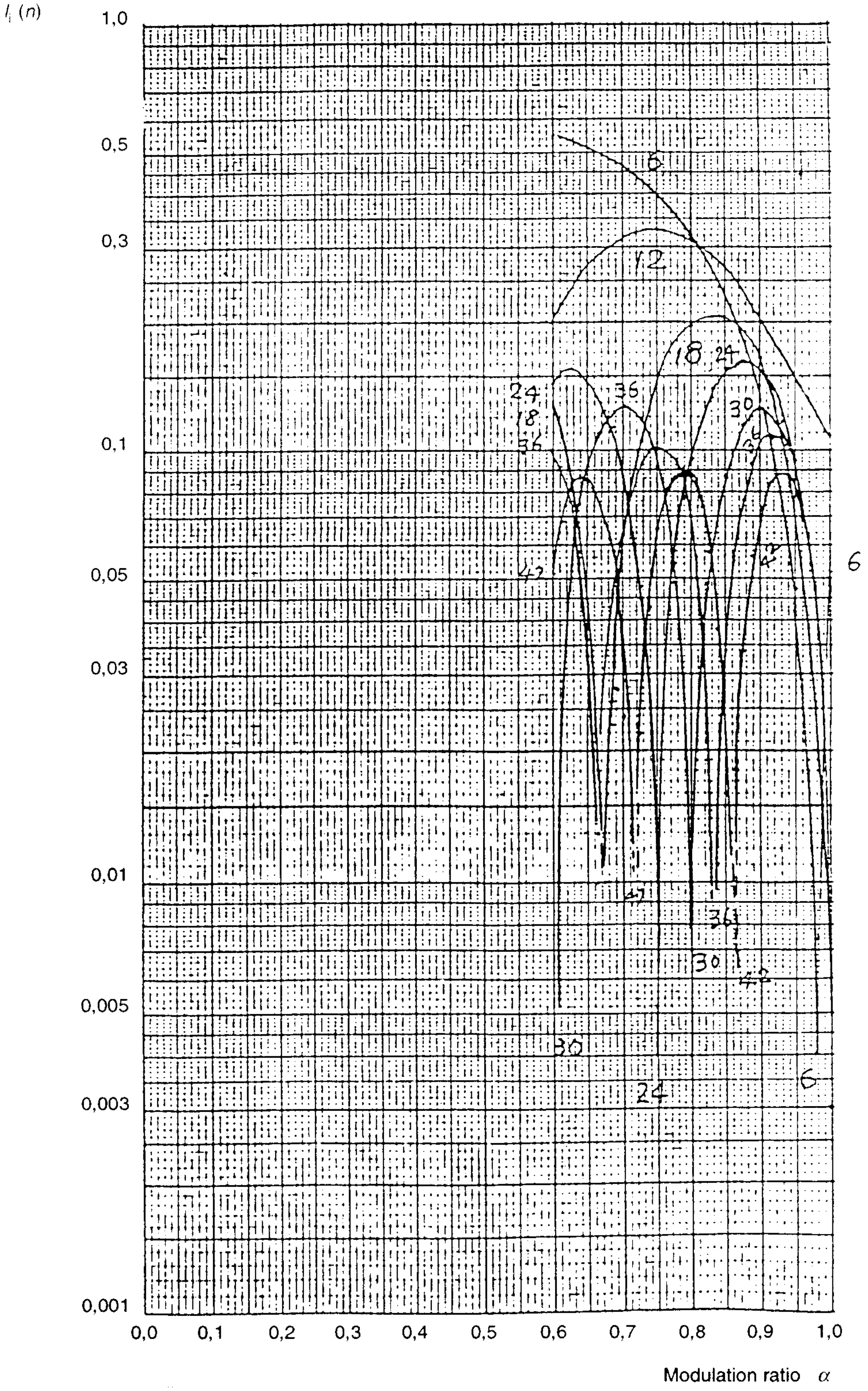


Figure A.13t

Figure A.13 *(continued)*

Modulation scheme:
rectangular-triangular modulation

Number of pulses: 1

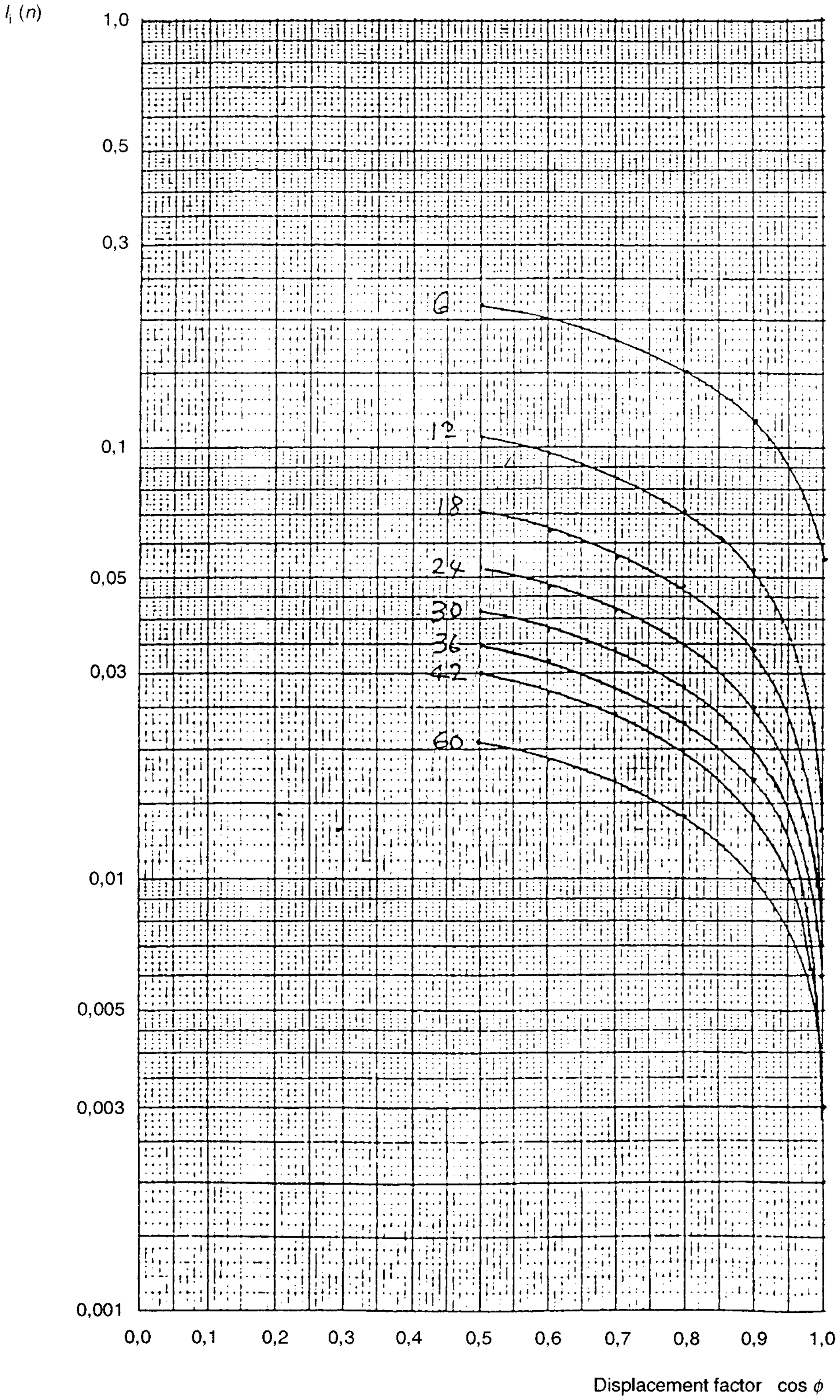


Figure A.13u

**Figure A.13** *(continued)*

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